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REPORT OF SURVEY OF THE TRUCKEE RIVER

R. L. O'Connell, et al

Public Health Service
Washington, D.C.

August 1963

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Report of Survey

of the

TRUCKEE RIVER

by

R. L. O'Connell
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Technical Advisory and Investigations Section
Technical Services Branch
Division of Water Supply and Pollution Control
Public Health Service
Department of Health, Education, and Welfare

August 1963

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TABLE OF CONTENTS

	Page
INTRODUCTION	1
DESCRIPTION OF SURVEY	2
HYDROLOGY	5
DISSOLVED OXYGEN AND TEMPERATURE	6
NUTRIENTS	11
BIOCHEMICAL OXYGEN DEMAND	16
EVALUATION OF PHOTOSYNTHETIC ACTIVITY	22
PREDICTION OF FUTURE CONDITIONS	35
SUMMARY AND CONCLUSIONS	41
BIBLIOGRAPHY	44

LIST OF TABLES

Table No.		Page
1	Sampling Stations	3
2	Climatological Data	7
3	Summary of Dissolved Oxygen and Temperature Results	9
4	Predicted versus Observed Minimum D.O. Truckee River (Station 4)	10
5	Average Chemical Quality	12
6	Average Nutrient Inflows	13
7	Summary of BOD Results	19
8	Calculation of Nighttime (P-R) by Finite Difference Method	25
9	Calculation of Daytime (P-R) by Finite Difference Method	26

LIST OF FIGURES

Figure No.		Follows Page
1	Truckee River Survey Area	2
2	Stream Flow - Truckee River, August, 1963 . .	6
3	Dissolved Oxygen (ppm) Truckee River, August 22, 1963	10
4	Dissolved Oxygen (% Saturation) Truckee River, August 22, 1963	10
5	Nitrogen Conversion in Truckee River	16
6	Deoxygenation Rate Curve Station 3 - Truckee River	18
7	Dissolved Oxygen in Truckee River, August 21-22, 1963	24
8	Dissolved Oxygen in Truckee River, August 22, 1963	24
9	Calculated Oxygen Consumption by Nitrification	28
10	Net Oxygen Added by Photosynthesis (P-R) ppm/hr Finite Difference Method	28
11	Diurnal Variation of (P-R) in Truckee River near Station 2B	28
12	Algae chamber as it appears in place in the river	30
13	Net Oxygen Added by Photosynthesis (P-R) ppm/hr Algae Chamber Method	32
14	Predicted Daily Minimum Dissolved Oxygen Station 4 - Truckee River	40

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INTRODUCTION

During July 1962 and August 1963 pollution surveys of the Truckee River in the vicinity of Reno, Nevada, were conducted by the Public Health Service at the request of the Nevada State Department of Health. The objective of these surveys was to obtain information on the river which was needed by the State and local communities for pollution abatement planning purposes. The oxygen resources of the river were of primary interest to the State and these surveys, therefore, were designed to provide a maximum amount of information on this particular aspect of river water quality.

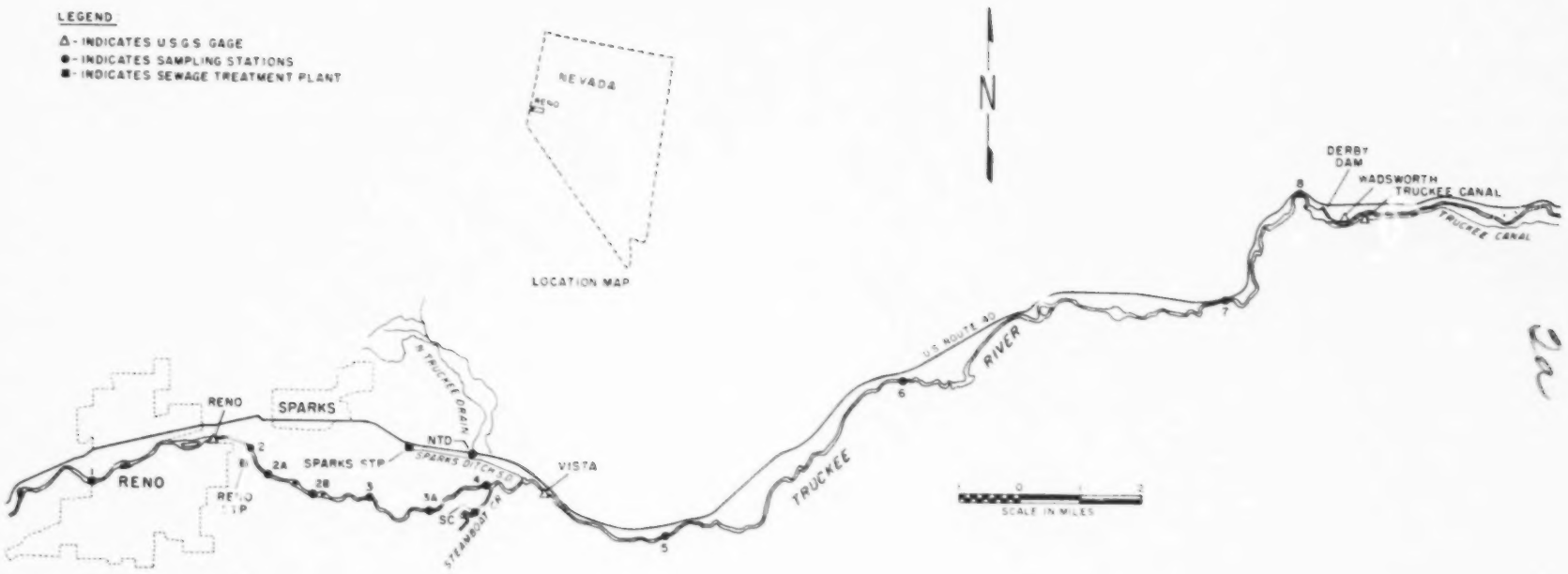
The 1962 survey revealed a considerable amount of useful information on the oxygen conditions existing in the river.[1] It was observed at that time that dissolved oxygen concentrations as low as 3.5 mg/l could be found at certain locations at the stream flow rates then occurring (150 cfs, Reno Gage). These low levels occurred during the early morning hours as the result, primarily, of nighttime respiration of the stream's dense algal population together with that of the other biota. The presence of algae causes a very large diurnal variation in the river dissolved oxygen content which serves to mask the changes caused by pollutional materials from waste discharges. As a result of this interference, it was not possible by conventional methods to predict the effect of future low stream flows and higher waste loadings on the stream's dissolved oxygen level. The information needed to make such predictions constituted a major objective of the first survey.

A method has been devised for making such predictions in situations where oxygen production and consumption by photosynthetic organisms is of major significance as was found in the Truckee River. Use of this procedure, however, requires more detailed information on dissolved oxygen changes with time of day and distance along the stream than was obtained during the first survey. The 1963 survey described here was specifically designed to provide this additional information. Because of the importance of nutrients to the growth of stream algae, information on the nitrogen and phosphorus levels in the river and its tributary flows and in waste discharges was obtained. The need for special studies of the biochemical oxygen demand reaction was indicated by the previous survey and these were also carried out.

This report presents the findings of the August 1963 survey together with a discussion of their significance. The factors contributing to the dissolved oxygen variations observed in the river are identified and evaluated. Based upon this evaluation, predictions of the effect of future increased waste loadings and reduced river flows on the dissolved oxygen content of the river are presented.

DESCRIPTION OF SURVEY

The survey was started on August 12, 1963, and continued for 12 days until August 24, 1963. Two separate schedules were used in collecting samples from 11 locations on the Truckee River, from two major irrigation return flows, and from the municipal sewage treatment plants at Reno and Spraks, Nevada. These sampling locations are shown in Figure 1 and described in Table 1. The first portion of the survey was designed to



TRUCKEE RIVER SURVEY AREA

FIGURE 1

Table 1

Sampling Stations

Field No.	Description	River Miles Below Reno Gage
1	Booth Street Bridge	-2.3
2	Glendale Street Bridge just above Reno Sewage Treatment Plant discharge point	0.5
RSTP	Reno Sewage Treatment Plant - Samples collected before chlorination at effluent of secondary clarifier	0.7
2A	200 feet below Pioneer diversion structure	1.0
2B	Extension of Marietta Way	2.0
3	Boynton Lane Bridge	2.8
3A	Below University Experimental Farm	4.2
4	Casci Ranch just opposite mouth of Steamboat Creek	5.7
SC	Steamboat Creek - Private vehicular bridge just above mouth of creek	5.7
SSTP	Sparks Sewage Treatment Plant - Effluent samples taken at open concrete box just ahead of discharge to effluent ditch	6.0
NTD	North Truckee Drain - At intersection of drainage ditch and U.S. Route 40	6.0
5	Vehicular bridge near Lockwood	8.7
6	Private vehicular bridge near Patrick Ranch	14.0
7	Bridge on road approaching Eagle-Picher Company	21.0
8	At railroad bridge above Derby Dam in impoundment backwater	23.8

provide information on the content of nutrients in a 25-mile stretch of the Truckee River, in the irrigation return flows, and the sewage treatment plant effluents. Samples were collected daily at various times during the day over a five-day period. These were analyzed for dissolved oxygen (D.O.), temperature, biochemical oxygen demand (BOD), temperature, alkalinity, pH, organic and inorganic forms of nitrogen, and total and orthophosphates. In addition, a time series analysis of the BOD reaction was made for most stations. All of the above tests were performed according to Standard Methods[2], although the BOD test was carried out on both untreated and pasteurized samples. Pasteurization was accomplished by heating the samples to 60°C and holding them at this temperature for 15 minutes. Following this procedure the samples were analyzed in the usual manner using standard dilution water containing 0.1% raw sewage seed. All D.O. and BOD tests were conducted in duplicate. D.O. samples were iced in the field and analyzed in the laboratory within four hours.

Analytical work was carried out in a mobile trailer located at the Sparks Sewage Treatment Plant. The laboratory facilities at the treatment plant were also utilized. Samples to be analyzed for organic nitrogen content were acidified and shipped to the Taft Sanitary Engineering Center in Cincinnati, Ohio.

During the second portion of the survey an intensive study was conducted of the five-mile stretch of stream from Station 2 to Station 4. During the 48-hour period beginning at noon, August 21, the six river stations in this stretch (as described in Table 1) and the Reno Sewage Treatment Plant effluent were sampled at approximately two-hour intervals.

Each sample was analyzed for D.O. and temperature and six hour composites were prepared for BOD analysis. With the exception of the BOD samples for this intensive study, all samples collected during the survey were grab samples.

The time of flow between stations in this stretch of the river was measured by the use of a fluorescent dye tracer (Rhodamine B) as described in the 1962 survey report. Stream cross sections were obtained at approximately 800-foot intervals between Station 2 and Station 4. Sewage treatment plant flows were recorded and field measurements were made of the two major irrigation return flows. The rate of photosynthetic oxygen production and consumption by respiration of the stream's algal population was measured in the stream in specially constructed chambers. The density of algal growth in the stretch from Station 2 to Station 4 was estimated.

HYDROLOGY

During August of 1963 the Truckee River flow was at normal levels as measured by the U. S. Geological Survey gaging stations at Reno and Vista (see Figure 1). The monthly average flow as depicted in Figure 2 increased from 203 cfs at the Reno Gage to 299 cfs at the Vista Gage, 6.4 miles downstream. This expected increase in flow over this stretch is attributable to four tributary inflows - two waste discharges and two irrigation return drains. The monthly flow contributions from these sources are shown below in downstream order:

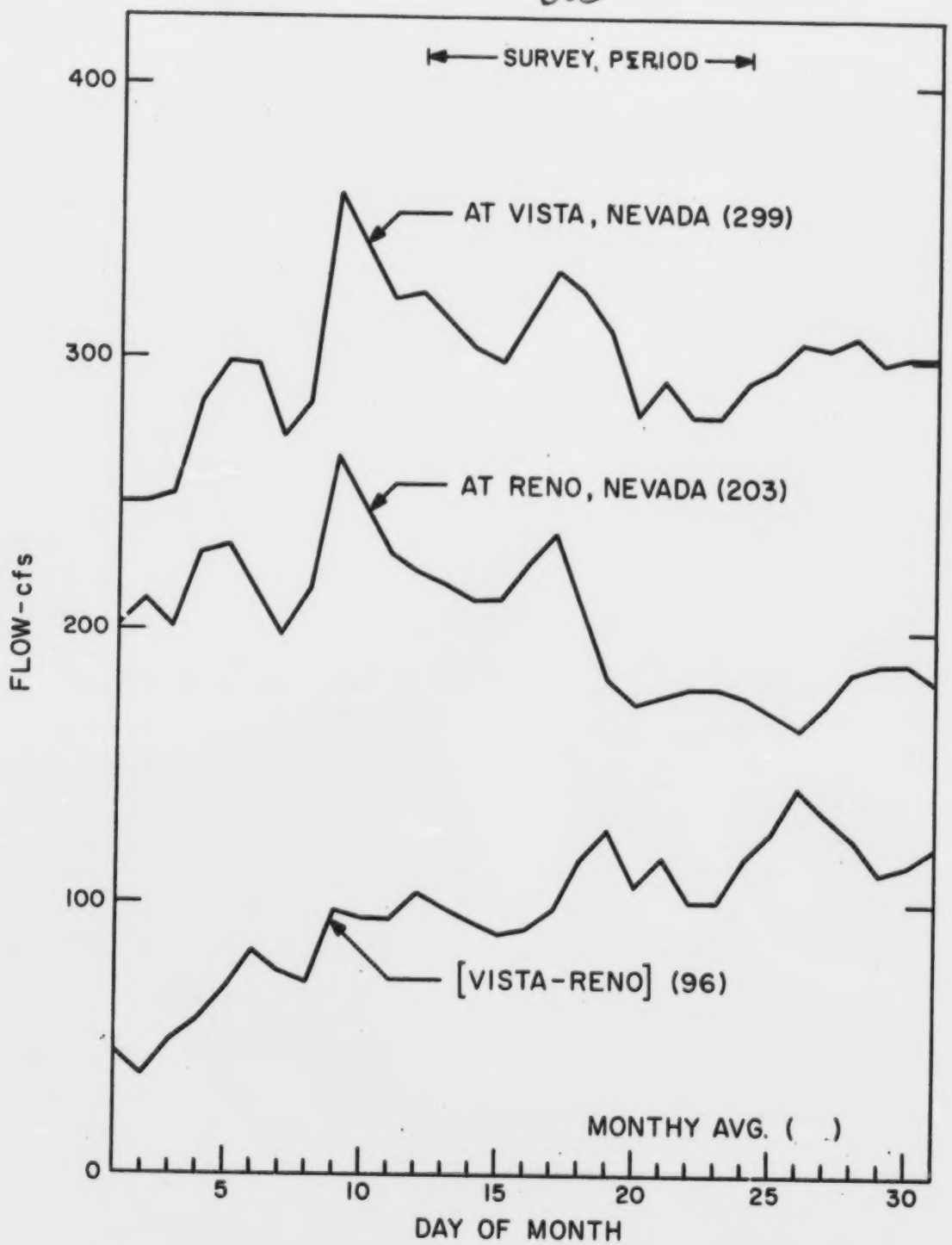
Reno Sewage Treatment Plant	17.9 cfs
Steamboat Creek	48.
Sparks Sewage Treatment Plant	7.6
North Truckee Drain	23.
	96.5

The flows from the two treatment plants were fairly consistent during the month while the combined flow from the two drains varied from 25 cfs at the beginning of August to a maximum of 140 cfs near the end of the month. During the survey period the total inflow to the river between the Reno and Vista Gages was at, or slightly above, the monthly average value of 96 cfs. The values given above for the flows from the drains were based on a series of flow measurements made during the survey period. During that time the Steamboat Creek flow varied from 34 to 58 cfs while the North Truckee Drain flow ranged from 14 to 31 cfs. Flow in the North Truckee Drain was measured and sampled where it crossed Highway 40 which is upstream of the entry of the Sparks Sewage Treatment Plant effluent into the drain.

River flows during the 1963 survey were approximately 50 cfs higher than those occurring during the July 1962 survey. No precipitation occurred during the survey period. This and other pertinent climatological data are given in Table 2.

DISSOLVED OXYGEN AND TEMPERATURE

Dissolved oxygen and temperature measurements were obtained from the Truckee River at 11 locations as well as from Steamboat Creek, North



STREAM FLOW - TRUCKEE RIVER
AUGUST, 1963

FIGURE 2

Table 2

Climatological Data

U.S. Weather Bureau, Reno, Nevada, August 1963

Date	Air Temp. °F Min.	Air Temp. °F Max.	Precipitation (inches)	Aver. wind Speed (mph)	% of possible sunshine
12	48	90	0	5.8	100
13	46	90	0	5.8	100
14	43	91	0	5.6	100
15	41	94	0	4.7	100
16	40	94	0	5.4	100
17	46	90	0	7.1	100
18	36	90	0	5.8	100
19	36	89	0	6.4	100
20	36	87	0	4.9	100
21	36	85	0	5.4	96
22	39	82	0	6.5	100
23	37	78	0	7.5	79
24	34	79	0	6.9	100

	August 1	August 31
Sunrise	5:58 A.M.	6:25 A.M.
Sunset	8:10 P.M.	7:31 P.M.

Truckee Drain, and the effluents from the two sewage treatment plants. A summary of the results of these measurements is presented in Table 3. The greatest number of samples were collected from the stream at six stations in the five-mile stretch from Station 2 to Station 4 and from the Reno plant effluent. All of these locations were sampled approximately every two hours around the clock for two days. The remaining stations were sampled six times; thus, the information obtained for these stations is not complete enough to fully describe the variations in D.O. and temperature throughout the day.

At the stations studied most intensively the wide diurnal range in dissolved oxygen observed was considered to be indicative of photosynthetic activity. A range of approximately 5 mg/l from the minimum to the maximum values was found at Station 3, 3A, and 4. The minimum observed value in the Truckee River was 4.5 mg/l at Station 4 and the maximum value, 9.9 mg/l, was found at Station 3A. These minimum and maximum values were recorded at approximately 4:00 a.m. and 2:00 p.m., respectively. Location and time of occurrence of these high and low values were the same as that found in the 1962 survey. The diurnal range in D.O., however, was not as great as found at that time, the minimum value being higher by one milligram per liter and the maximum value being lower by several milligrams per liter in August 1963. This change is attributable in part to the slightly increased stream flow during the 1963 survey. Equally important was an apparent reduction in photosynthetic activity, probably due to the disturbance caused by bulldozer operations in this stretch of the river during and just prior to the survey and the lower stream temperatures

Table 3

Summary of Dissolved Oxygen and Temperature Results

Station*	No. of Samples	D.O. (mg/l)			Temperature °C		
		Min.	Median	Max.	Min.	Mean	Max.
1	6	8.1	8.6	8.9	14.0	16.6	20.5
2	36	7.6	8.4	9.8	14.0	17.0	20.0
2A	28	6.7	7.9	9.4	13.5	17.1	19.8
2B	28	5.1	7.0	9.2	13.5	17.5	20.8
3	36	4.9	6.9	9.8	14.0	17.7	22.0
3A	30	4.9	6.7	9.9	14.3	17.6	21.3
4	37	4.5	6.9	9.3	14.0	18.0	22.0
5	6	5.4	5.8	6.6	17.5	18.2	19.0
6	6	5.9	6.6	7.1	18.5	19.4	20.5
7	6	6.0	6.2	7.2	17.5	19.7	21.5
8	6	5.5	6.0	6.4	18.0	19.4	21.0
RSTP	34	0.0	2.0	2.5	20.5	22.6	25.5
SSTP	6	2.0	4.1	5.0	18.0	19.6	21.0
SC	6	5.3	5.8	7.4	14.5	18.0	22.5
NTD	6	3.4	5.7	8.0	16.5	17.8	20.5

* Identified in Table 1.

encountered in the 1963 survey. The mean stream temperatures at Stations 3 and 4, for example, were in each case 2.4°C lower than those encountered in the previous survey. This was brought about by the record-breaking low air temperatures occurring during the survey as shown in Table 2. The daily minimum D.O. observed at Station 4, however, was near the values predicted in the 1962 survey report as a function of stream flow (see Table 4).

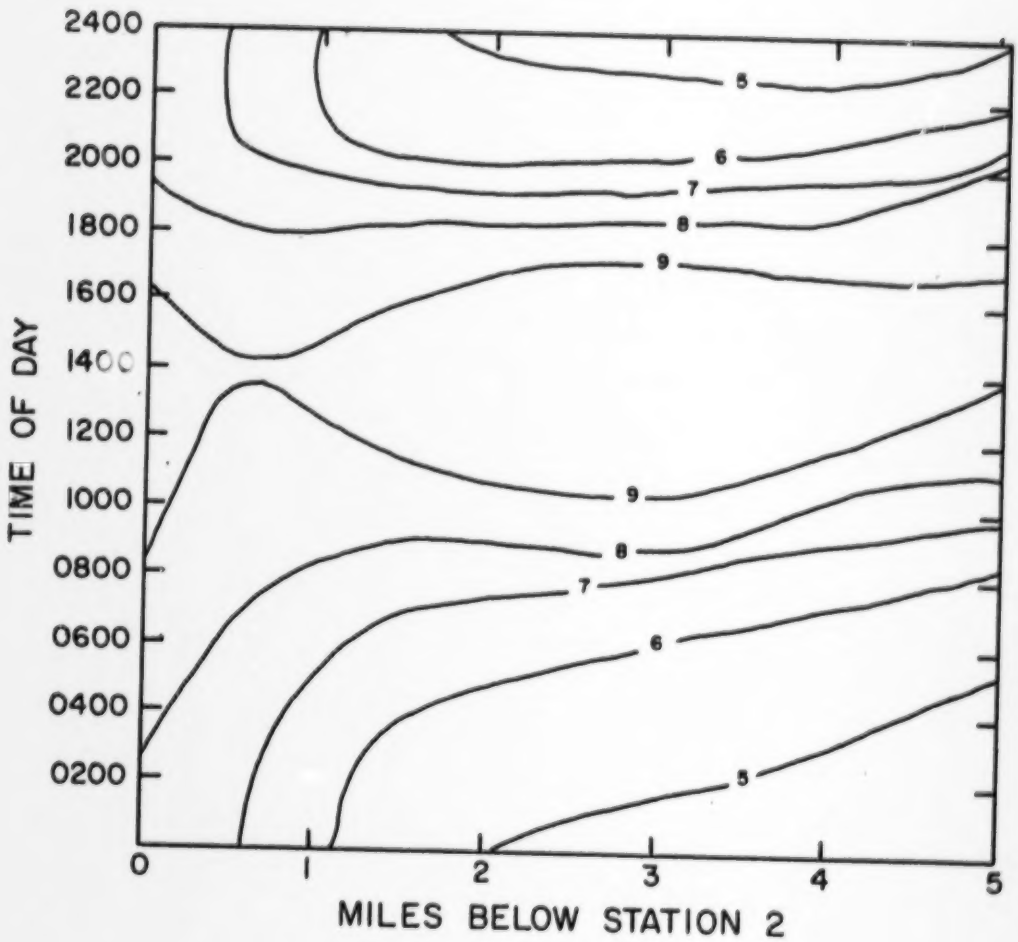
Table 4

Predicted versus Observed Minimum D.O.
Truckee River (Station 4)

Date	Time	Flow (Reno Gage)	D.O. (mg/l) Predicted* (1962)	D.O. (mg/l) Observed (1963)
8/13/63	0500	217	4.7	4.5
8/20/63	0200	173	4.1	4.65
8/22/63	0220	179	4.2	4.75
8/23/63	0305	179	4.2	4.70

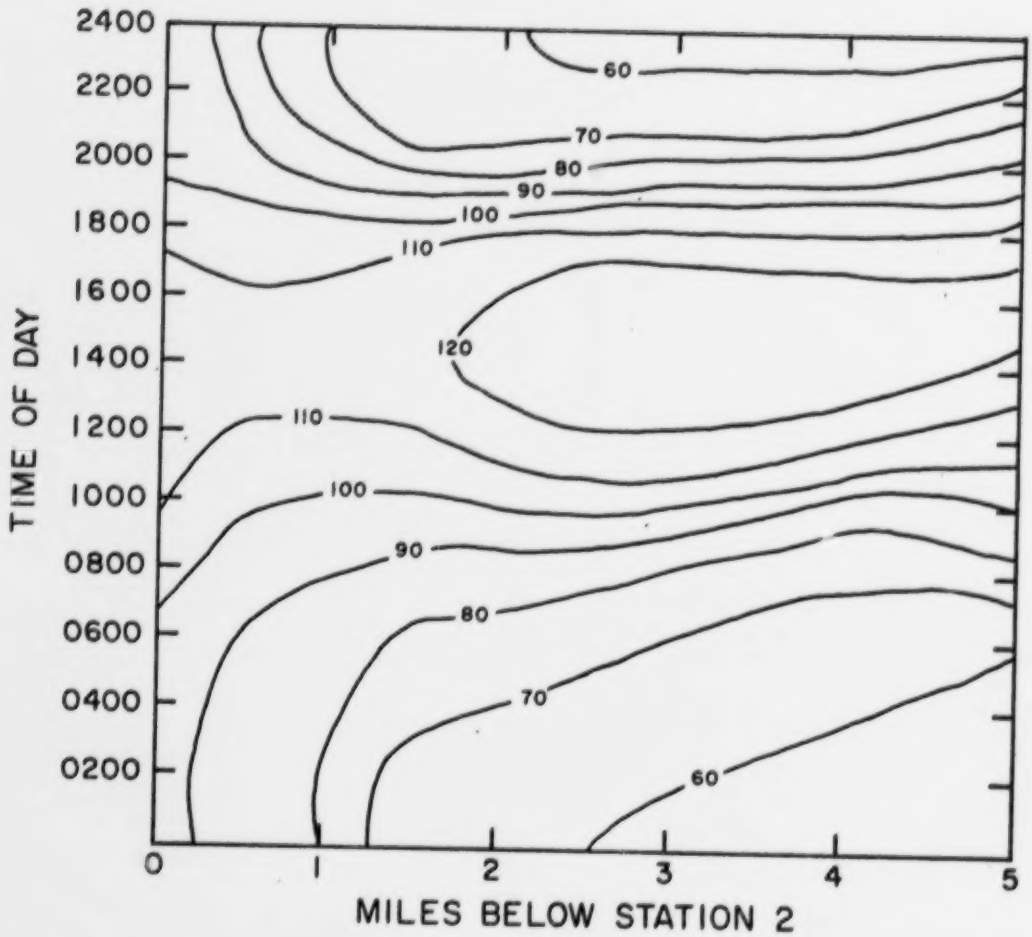
* Reference 1, Figure 20

In order to present a more complete description of the dissolved oxygen variations encountered, the three-dimensional plots shown in Figures 3 and 4 were prepared. From these figures the dissolved oxygen conditions at any location and time of day may be obtained. A vertical section through these figures will show the diurnal variations at a



DISSOLVED OXYGEN (ppm)
TRUCKEE RIVER AUGUST 22, 1963

FIGURE 3



DISSOLVED OXYGEN (% SATURATION)
TRUCKEE RIVER, AUGUST 22, 1963

FIGURE 4

given station, while a horizontal section will give a synoptic picture of the variation in dissolved oxygen with distance downstream at any given time of day. A diagonal section with slope equal to the stream velocity would show the changes occurring in a given mass of water as it traveled downstream. This latter concept is used in subsequent discussions of the factors contribtuing to the observed D.O. changes.

NUTRIENTS

In many natural waters the major factor limiting the prolific and often damaging growth of algae is the absence of sufficient quantities of the fertilizing elements, nitrogen, phosphorus, and possibly other growth stimulating materials, found in treated sewage in trace amounts. It would appear that this description fits the Truckee River as well. The river as it enters the Reno metropolitan area at Station 1 has a well-balanced biological population indicative of a healthy, unpolluted aquatic environment.[1] The nitrogen and phosphorus content of the river water at this station (Table 5) is relatively low which is in keeping with the stream biology. The nutrient levels found here and at Station 2 are similar to concentrations found in the mountain streams tributary to Lake Tahoe which is the source of the Truckee River. In those streams the average total nitrogen and soluble orthophosphate concentrations have been reported to be 0.3 and 0.06 mg/l, respectively.[3] In comparison, the corresponding values are 0.3 and 0.08 mg/l in the Truckee both above the city of Reno (Station 1) and below the city but above the Reno Sewage Treatment Plant (Station 2). Below this point the largest of four major nutrient sources, the Reno plant, discharges to the river. As shown in

Table 5

Average Chemical Quality
(mg/l)

River Stations (a)	Org-N	NH_4-N	NO_2-N	NO_3-N	PO_4-P Ortho	PO_4-P Total	pH	Total Alkalinity
1	0.15	0.15	0.01	< 0.2	0.08	0.16	7.6	44.
2 (b)	0.15	0.13	0.01	< 0.2	0.08	0.18	7.9	49.
3	0.44	1.14	0.07	< 0.2	1.76	2.21	7.6	59.
4 (c)	0.25	0.96	0.09	< 0.2	1.58	1.93	7.6	52.
5	0.51	0.84	0.09	0.2	1.73	2.31	7.8	86.
6	0.70	0.6	0.17	0.2	1.78	2.16	7.8	84.
7	0.59	0.2	0.13	0.4	1.35	1.71	7.8	84.
8	0.56	0.16	0.12	0.3	1.29	1.80	7.9	83.
Tributary Stations (a)								
RSTP	3.89	15.8	0.01	< 0.2	20.4	25.0	7.3	154.
SSTP	3.14	11.0	0.03	0.2	13.5	19.3	7.5	164.
SC	0.62	0.18	0.02	< 0.2	0.86	1.21	8.0	117.
NTD	0.71	0.5	0.02	< 0.2	0.34	0.46	7.9	114.

(a) Description given in Table 1.

(b) RSTP enters between Stations 2 and 3.

(c) NTD, SSTP, and SC enter between Stations 4 and 5.

Table 6, this source accounts for about two-thirds of the 1.5 tons each of nitrogen and phosphorus which are added daily to the Truckee River just below Reno. The concentration of nitrogen and phosphorus in its various forms in the river reflects this addition. At the next downstream station (Station 3) the total nitrogen content is five and a half times higher than found just above the Reno discharge. This increase occurs primarily in the ammonia nitrogen with smaller rises in the organic and nitrite forms. No significant increase in the nitrate level was noted at Station 3. Similarly, the total phosphorus content increased tenfold, the increase being largely as orthophosphate, a form most readily available to aquatic organisms.

Table 6

Average Nutrient Inflows
(lbs/day)

Tributary Stations	Nitrogen					Phosphorus	
	Org-N	NH_3-N	NO_2-N	NO_3-N	Total N	Soluble Ortho PO_4	Total PO_4
RSTP	382	1370	1	20	1773	1970	2420
SSTP	101	447	1	11	560	554	792
SC	168	59	5	50	282	218	307
NTD	284	152	3	< 29	468	42	57
Totals	935	2028	10	< 110	3083	2784	3576

From Station 3 to Station 4 no significant amount of nutrients is added to the stream. As a result of bacterial action, however, changes may be observed in the various forms of nitrogen. As described by the

familiar nitrogen cycle, the organic form of nitrogen will in time be decomposed to ammonia nitrogen by bacterial action. The ammonia form, in turn, is oxidized to the nitrite and finally the nitrate form of nitrogen. Upon being converted to nitrates, the nitrogen is in a form which in the presence of sunlight is most readily utilized[4] in the production of living plant matter such as the algae found in great abundance in the Truckee River below Station 2. It has been demonstrated[5] that some of the microscopic algal species immediately take up nitrogen in the form of ammonia and do not require its oxidation to the nitrate form. Whether this is true of the larger alga (Oscillatoria) predominant in the Truckee River is not actually known. Although it has been assumed in this case that nitrogen loss from the stream followed oxidation to the nitrate form, most of the conclusions subsequently reached would not be significantly altered if the ammonia form were utilized directly.

Algal growths cannot proceed, however, unless phosphorus, and probably other elements in trace amounts, are available in addition to assimilable forms of nitrogen. The amount of phosphorus required to permit high growth rates is much less than the nitrogen requirement. Sawyer[6] has found that for algal blooms in certain lakes the critical level for phosphorus is 0.01 mg/l as soluble orthophosphate while the inorganic nitrogen concentration required is 0.30 mg/l. While these findings regarding lakes cannot be directly applied to flowing streams, it would seem from the data in Table 5 that phosphorus is present in the river below Reno in great excess of the probable amount required to permit rapid growth. In fact, most of the 2800 lbs/day of PO_4-P discharged

to the river was not utilized by the aquatic organisms and 2000 lbs/day were found remaining at Station 8.

The 935 pounds of organic nitrogen added to the river below Reno were diminished only slightly by decomposition in the 25-mile stretch studied. The inorganic forms of nitrogen changed markedly, however, as shown in Figure 5. The ammonia content dropped off steadily and was accompanied by corresponding increases in the nitrite and nitrate forms of nitrogen. Furthermore, a steady loss of inorganic nitrogen from solution in the river water occurred such that one half of the total nitrogen added to the stream, or 1500 lbs/day, was removed between Station 2 and Station 8. This nitrogen loss is presumed to represent the quantity of nitrate nitrogen utilized in the production of algae and other aquatic plants. The rate of nitrogen loss throughout this 25-mile stretch was fairly uniform at 1.2 mg/l per day.

The conversion of ammonia nitrogen through the nitrite step to nitrates is accomplished by autotrophic nitrifying bacteria under aerobic conditions. Oxygen is consumed in this process as described by the following reactions:

$$NH_4^+ + 1\tfrac{1}{2}\, O_2 \longrightarrow NO_2^- + 2H^+ + H_2O \qquad (1)$$

$$NO_2^- + \tfrac{1}{2}\, O_2 \longrightarrow NO_3^-$$

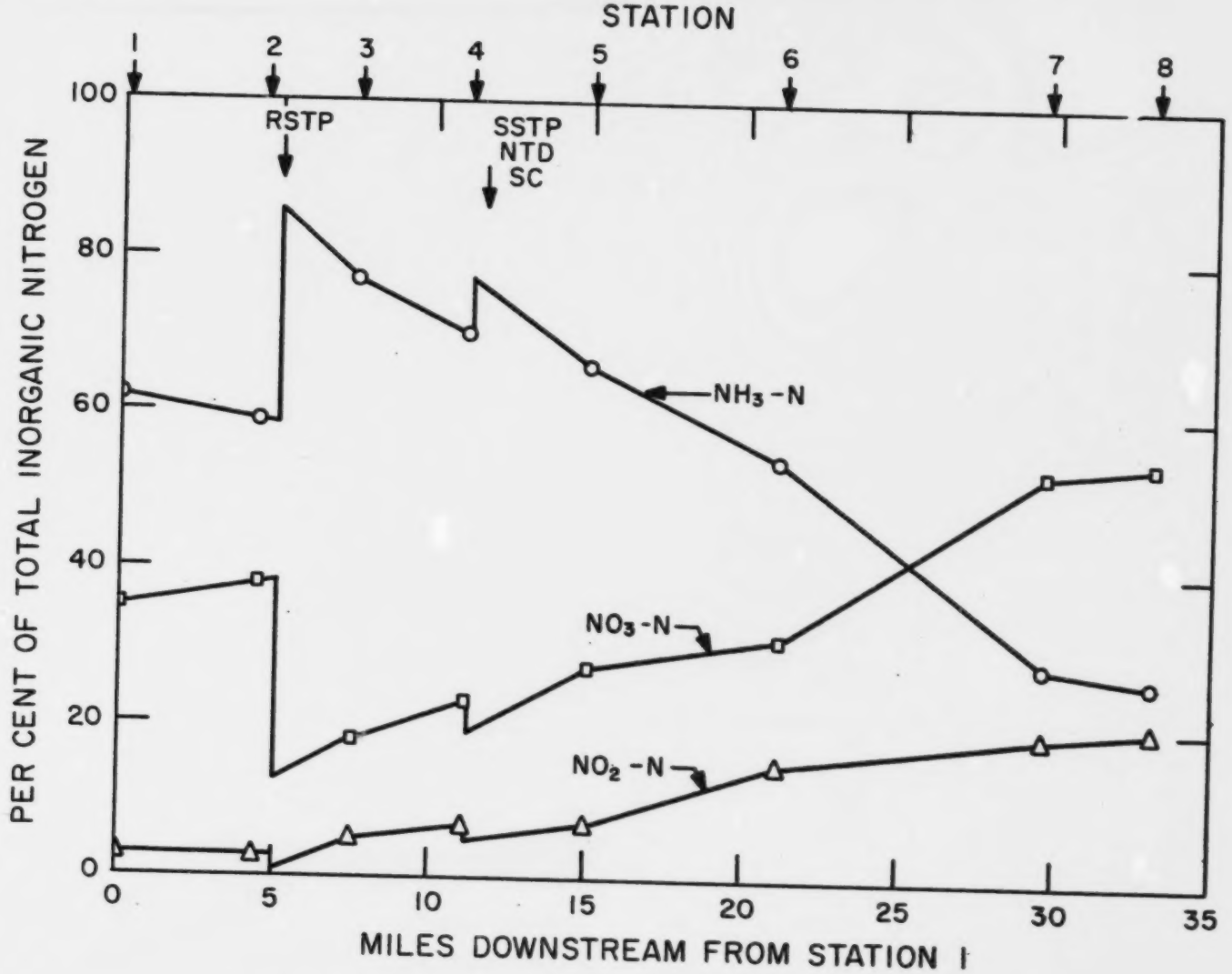
In the first reaction 3.43 parts by weight of oxygen are necessary for each part of nitrogen oxidized and in the second 1.14 parts by weight of oxygen are required. Thus, each mg/l of NH_3-N oxidized to NO_3-N will

represent the consumption of 4.57 mg/l of oxygen. As will be shown later, this source of oxygen demand is a significant factor in the oxygen balance of the Truckee River. It is potentially four times greater than the oxygen consumed in the first or carbonaceous stage of the biochemical oxygen demand (BOD) reaction in waste effluents discharged to the Truckee River.

BIOCHEMICAL OXYGEN DEMAND

The standard BOD test calls for incubation of a sample for five days to determine its oxygen uptake over that period. The information obtained from this test is of value only if the type of reaction and the rate at which this reaction is taking place are known. Ordinarily it may be assumed that the reaction is first order and that the reaction rate constant, k_1, if not otherwise known, is approximately 0.1 to 0.15 (Base 10). These assumptions are generally made when analyzing five-day BOD test data where information of only a general nature is desired. However, when more precise information is needed, as when attempting to conduct an oxygen balance for a particular river, it is necessary to verify both the assumption of reaction type and rate. This can be done as in the 1962 survey by incubating a series of bottles containing replicates of the same sample. Each day a duplicate set of the bottles is removed from the incubator and analyzed for their oxygen content. In this way the rate of oxygen consumption over time can be observed.

In conducting such a time series on samples taken from the Truckee River in 1962, it was observed that assumption of a simple first order reaction did not provide a satisfactory interpretation of five-day BOD



NITROGEN CONVERSION IN TRUCKEE RIVER

FIGURE 5

16a

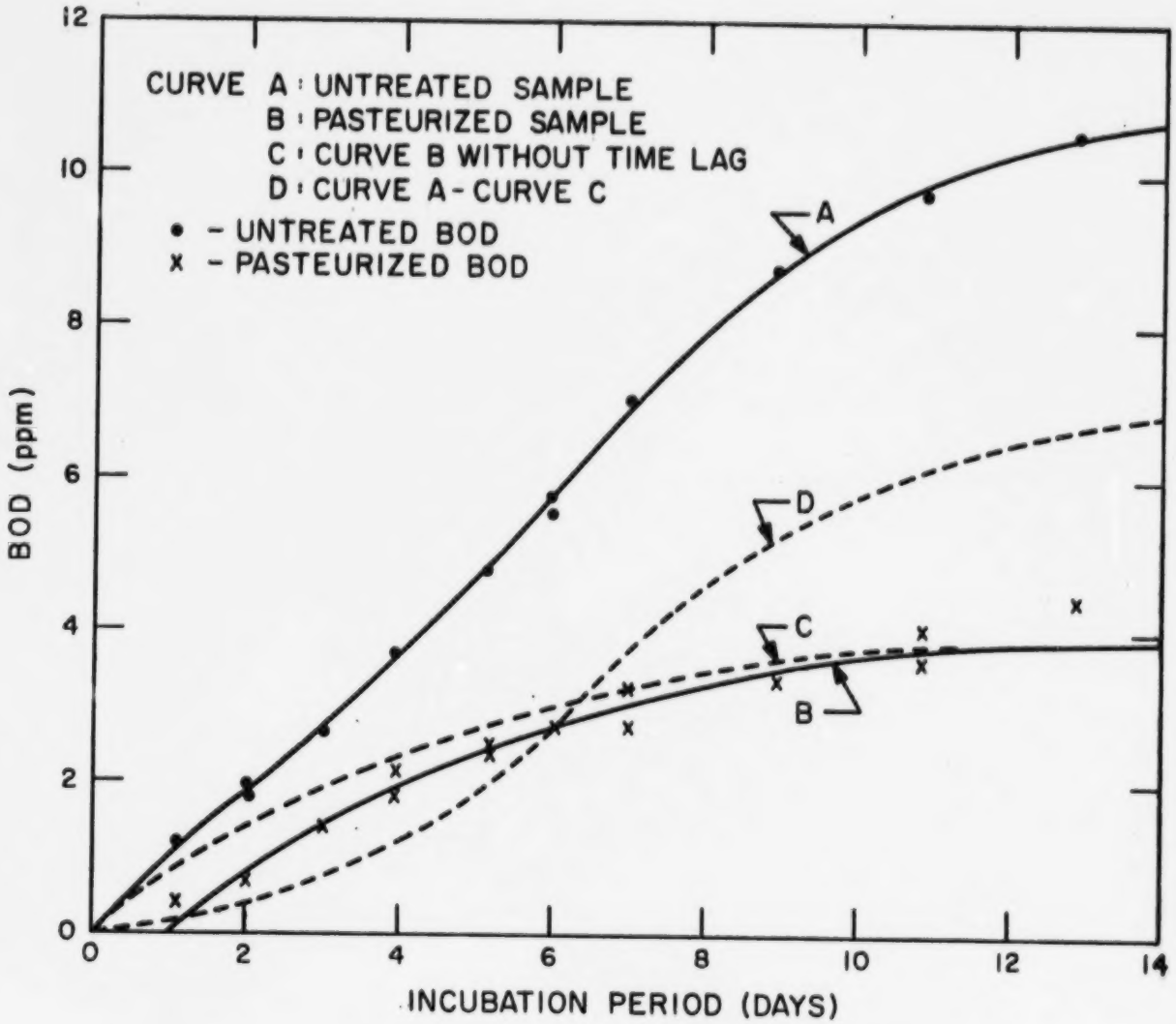
test results. The time series observations on stream samples indicated that nitrification began on either the first, second, or third day and was well underway by the fifth day. Thus, oxygen consumption measured over a five-day period by the standard BOD test included a substantial consumption due to the oxidation of nitrogenous materials in the second stage of the BOD reaction. This made the analysis of five-day BOD test results more difficult. For example, the BOD load in the stream below the Reno Sewage Treatment Plant outfall was almost double the amount discharged on the basis of five-day BOD test results. This occurred because the Reno effluent did not exhibit nitrification within five days while the stream samples consistently did so.

In order to perform a satisfactory balance of BOD loadings, it was necessary to separate the first stage or carbonaceous demand from the second stage or nitrogenous demand. An attempt was made to do this by analysis of the time series BOD curve for the river stations. However, because nitrification commenced at such an early stage it was not possible to separate the two stages in a satisfactory manner. During the 1963 survey a technique was used to separte the two stages which employed the pasteurization of the sample prior to incubation. According to Sawyer[6], the pasteurization step could be expected to destroy or at least greatly reduce the number of nitrifying bacteria present in the sample. After adding raw sewage which contains few nitrifying bacteria, as a seed, the first stage demand should be expected to proceed without interference from the second or nitrifying stage until well beyond the five-day incubation period. The curves shown in Figure 6 illustrate the effect of

pasteurization on the BOD reaction. The pasteurized sample data, after an initial lag period, may be fitted quite well by the first order reaction equation. Thus, it is possible to obtain from the pasteurized sample the ultimate first stage oxygen demand and the reaction rate constant, k_1.

Curves such as those shown in Figure 6 were obtained for every river station and a similar time lag on the pasteurized samples was observed at each of the eight stream sampling locations. The treatment plant samples, however, showed no change due to pasteurization indicating that nitrification was not taking place within the plants. Allowing for the time lag it was possible to fit every stream sample following pasteurization with a first order reaction curve. Since a primary objective was to obtain or determine the ultimate first stage demand and the reaction rate constant, k_1, the pasteurization procedure served the purpose quite well.

All five-day BOD tests were run on both pasteurized and untreated samples, although the pasteurized sample, in this case, actually provided the more useful information. A summary of the five-day BOD test results is shown in Table 7. It can be seen that pasteurization had little effect on samples from Station 1 and Station 2 which are above the entrance of waste discharges. Samples from Station 3 and from all other stations downstream from the Reno outfall sewer yielded very different results from the pasteurized and untreated BOD tests as might be expected. The ratio of the pasteurized results to the untreated results is fairly consistent at Stations 3 through 8 inclusive. This ratio ranged from 33 to 46% of these stations and averaged 40%. With this information it is then



DEOXYGENATION RATE CURVE
STATION 3 - TRUCKEE RIVER

FIGURE 6

Table 7

Summary of BOD Results

Station(a)	No. of Samples	Mean BOD_5 (mg/l)		Past. BOD_5 / Std. BOD (Median)	$k_1(days^{-1})$
		Standard	Pasteurized		
1	6	1.2	1.1	0.88	0.24
2	6	1.6	1.2	0.70	0.24
3	6	6.1	2.6	0.44	0.11
4	6	5.8	2.6	0.46	0.13
5	6	6.3	2.4	0.39	0.15
6	6	6.0	1.9	0.33	0.13
7	6	4.	1.5	0.39	0.09
8	6	3.5	1.4	0.40	0.13
RSTP	4	31.	29.	0.96	0.20
SSTP	6	59.	61.	0.99	0.12
SC	5	2.9	1.5	0.52	--
NTD	5	2.5	1.5	0.58	--

(a) Description given in Table 1.

possible to more satisfactorily interpret the results obtained from the standard five-day BOD test. The ultimate first stage BOD, L_u, present at any of the stream stations below Reno can be estimated from the standard BOD test results by the following calculation:

$$L_u = \frac{ay_5}{1-10^{-k_1(5-t)}} \qquad (2)$$

where

y_5 = observed five-day BOD, mg/l

a = ratio past BOD_5:std. BOD_5 ($\approx$ 0.40)

k_1 = reaction rate constant

t = time lag of pasteurized sample ($\approx$ 1.0)

The k_1 values to be used in this calculation are also shown in Table 7. These were obtained from analysis of the pasteurized time series of BOD measurements and all fell in the range from 0.09 to 0.15.

By the methods described above the first or carbonaceous stage of the BOD reaction can be fairly well evaluated, but the amount of the second stage demand and when and where it is exerted in the stream is still unanswered. It is obvious from examination of Figure 6 that the oxygen requirement during the second stage greatly exceeds that during the first stage, possibly by as much as the factor of 4. The total amount of oxygen required for stablization of a given sample including both the first and second stage may be determined in several ways. One method would be to incubate a sample for as long a period as may be necessary, possibly several weeks so as to carry out the oxidation to completion. Another method would be to fit a growth type (S-shaped)

curve to the second stage demand, i.e., to the difference between the total or untreated demand and the pasteurized or first stage demand. This curve could then be extrapolated to yield an estimate of the ultimate second stage demand. A third possibility which was used in this study, is to analyze samples for their ammonia, nitrite, and nitrate nitrogen content. The calculated combining weight of oxygen required to oxidize the ammonia and nitrite nitrogen present to the nitrate form provides an extimate of the second stage demand. While any of these procedures will yield a useful estimate of the total second stage demand, the rate at which this demand is exerted in the stream must also be determined. While it is possible to estimate the reaction rate from the observed oxygen uptake in the BOD bottle, there is no assurance that this same rate will prevail in the stream. In fact, from the observed nitrogen concentrations already presented it is apparent that what happens in the stream is not reproduced in the laboratory bottle. In Figure 6 it would appear that the second stage is not exerted to a significant degree until the second or third day. However, from Table 5 and Figure 5 it can be seen that in the stream oxidation of the ammonia nitrogen to nitrite nitrogen commenced immediately below the Reno Sewage Plant outfall. This conversion of ammonia nitrogen to the oxidized forms was, in fact, largely completed at Station 8 which is approximately one day's flow below the Reno discharge. Thus, any second stage reaction rate obtained from laboratory data on oxygen uptake would be of questionable value for application to the stream in this case.

Some differences may also be noted between the course of the first stage reaction as observed in the laboratory and the rate of removal of carbonaceous demand from the stream. Here the discrepancy is much less however and the first order reaction seems to be followed quite well in both cases. In the 1962 survey the rate constant descriptive of the rate of removal BOD from the stream, k_r, was found to exceed the laboratory deoxygenation rate constant, k_1, and was estimated to be 0.31. Although far less stream BOD data were collected in this survey, a similar higher rate of removal from the stream was also indicated.

EVALUATION OF PHOTOSYNTHETIC ACTIVITY

In order to predict the stream's dissolved oxygen content under future conditions of waste loading and stream flow, it is desirable to have a mathematical model of the factors influencing the oxygen content of the stream. The model most often employed in stream studies, the oxygen sag formula, is inadequate in its simplest form to describe changes in oxygen content associated with the photosynthesis and respiration of the stream's aquatic biota. However, by a slight modification of the formula involving the addition of a term to reflect photosynthetic effects, the oxygen sag formula can be adapted satisfactorily to a stream such as the Truckee River. Equation 3 is the modified oxygen sag formula used in this case.

$$\frac{dD}{dt} = K_1L - K_2D - (P-R) \qquad (3)$$

where

D = oxygen deficit (mg/l)

L = ultimate first stage oxygen demand (mg/l)

t = time of flow (hours)

K_1 = deoxygenation rate constant ($hours^{-1}$)

K_2 = reareation rate constant ($hours^{-1}$)

(P-R) = net oxygen added or removed by algal activity (mg/l/hr)

If the (P-R) term is considered to be constant, a solution to Equation 3 is:

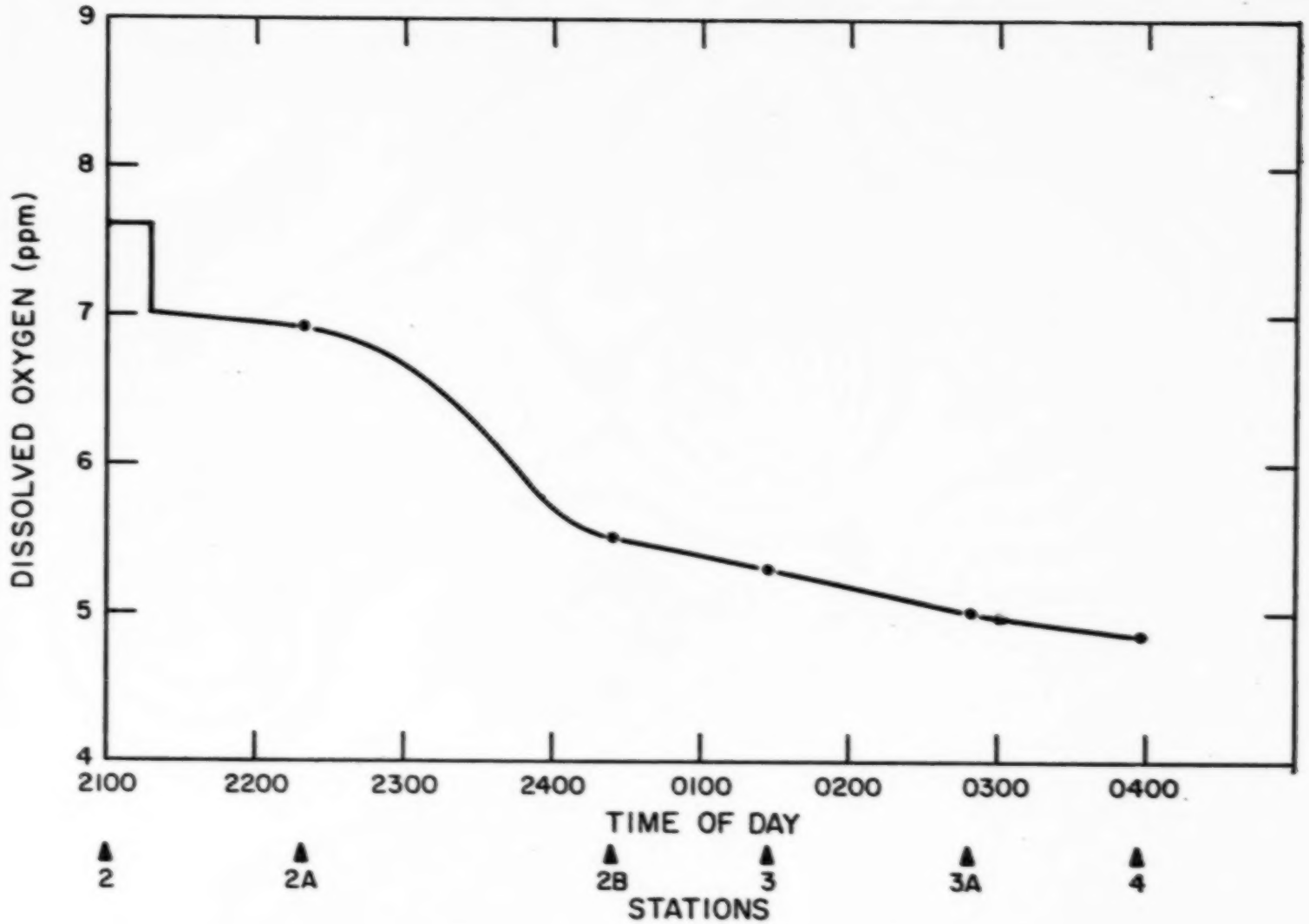
$$D_t = \frac{K_1 L}{K_2 - K_1} (e^{-K_1 t} - e^{-K_2 t}) - \frac{(P-R)}{K_2} (1 - e^{-K_2 t}) + D_a e^{-K_2 t} \qquad (4)$$

The terms K_1, L, and D are known from observed stream conditions and laboratory data and K_2 may be estimated using any one of several formulas available. In order to use Equation 4 for prediction purposes, the term (P-R) must be evaluated. Two different methods were used in this study to evaluate (P-R). The first involved the analysis of the observed stream D.O. data and required that an estimate of K_2 be made. The second estimate of (P-R) was made independently by a more direct technique which involved the measurement in the stream of the rate of oxygen change brought about by a known mass of algae housed in a test chamber.

In order to obtain the data necessary to apply the first method, the stream was sampled for dissolved oxygen and biochemical oxygen demand every two hours over a 48-hour period at six locations in the five-mile stretch between Station 2 and Station 4. The Reno Sewage Treatment Plant effluent discharge was also monitored for dissolved oxygen content and BOD during this period. With these data it was possible to construct a D.O. versus time of day plot for each station. The time of flow between each of these stations was measured by the use of a fluorescent dye tracer

(Rhodamine B). Knowing the time of flow from station to station it is possible to construct the time history of a hypothetical unit volume of water as it traverses the five-mile stretch of stream from the Reno Plant outfall to Station 4. For example, for two stations one hour apart in time of flow (measured by displacement) it may be assumed that the water passing the upstream station at one o'clock will pass the downstream station at two o'clock. Continuing in this manner downstream it would be possible to construct a curve reflecting the change in D.O. content of this unit volume of water as it traveled downstream. This concentration time history curve will, of course, be different depending upon the time at which the unit volume entered the stretch under study. In order to obtain information covering the full daily cycle, 24 curves, such as those described above, were constructed for a unit volume of water entering the stretch each hour of the day. Figures 7 and 8 illustrate two of these curves. In Figure 8 the mass of water entered the stretch at 9:00 a.m. at which time the D.O. was rising. It continued to rise as the water passed through the stretch until about 2:00 p.m. when the peak concentration had been reached and the D.O. then started falling. In Figure 7 water entered the stretch 12 hours later at 9:00 p.m. and the D.O. at that time was beginning to drop. It decreased steadily until a minimum D.O. value was reached at the end of the stretch at Station 4 at 4:00 a.m.

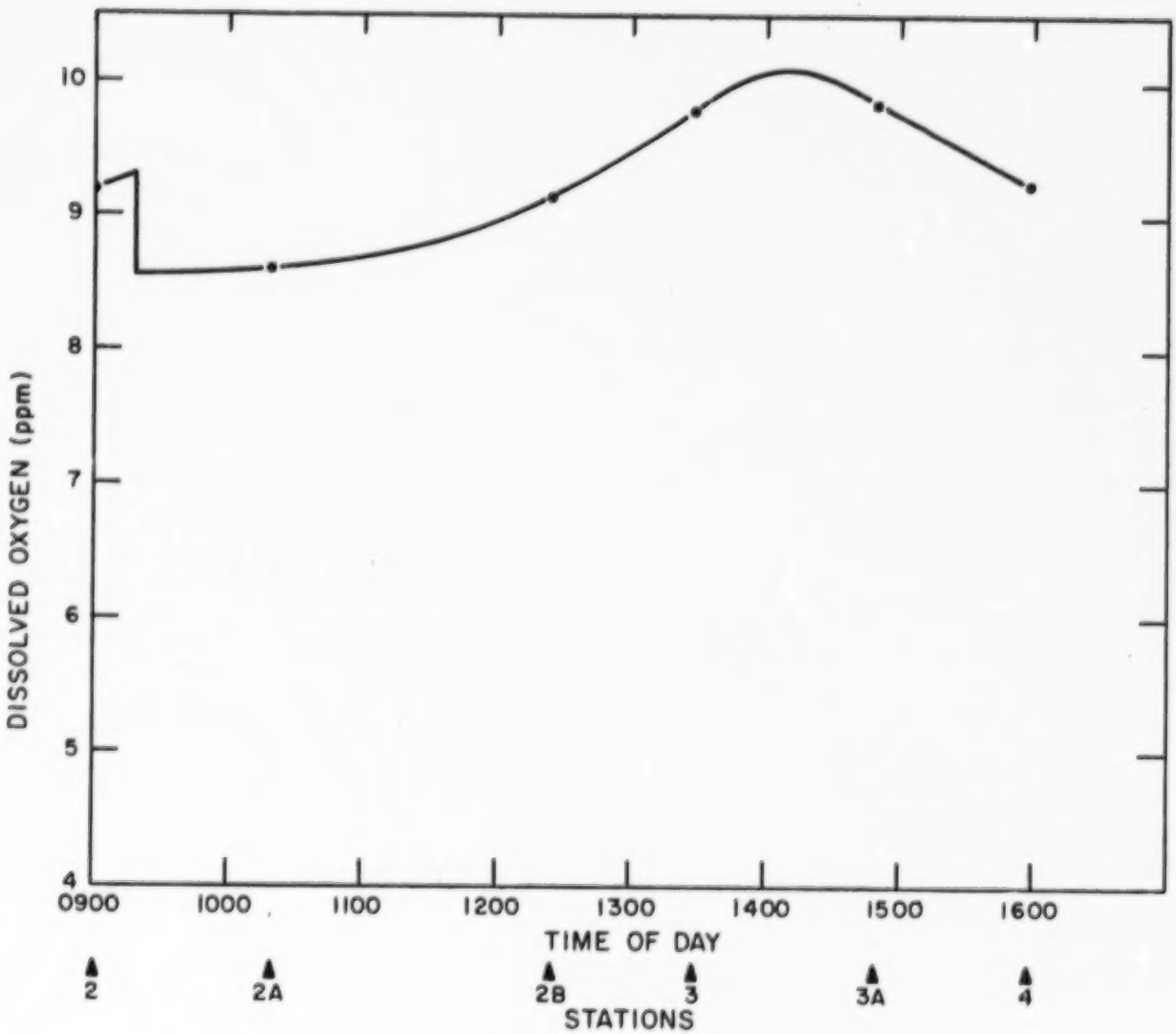
Equation 3 in its finite difference form and modified to include an estimate of nitrification was used to analyze the 24 curves described above. A typical analysis is shown in Table 8 for the curve in Figure 7. It can be seen that 13 values for (P-R) are obtained from the curve, one



DISSOLVED OXYGEN IN TRUCKEE RIVER
AUGUST 21-22, 1963

FIGURE 7

24a



DISSOLVED OXYGEN IN TRUCKEE RIVER
AUGUST 22, 1963

FIGURE 8

Table 8

Calculation of Nighttime (P-R) by Finite Difference Method

Time	D.O. (mg/l)	$\frac{\Delta c}{\Delta t}$ ($\frac{mg/l}{hour}$)	Temp. (°C)	C_s (mg/l) (a)	D (mg/l)	$\bar{D}$ (mg/l)	K_2 (hr^{-1})	K_2D ($\frac{mg/l}{hour}$)	K_1L (b) ($\frac{mg/l}{hour}$)	N (c) ($\frac{mg/l}{hour}$)	(P-R) ($\frac{mg/l}{hour}$)
2120	7.00		17.9	8.15	1.15						
2200	6.93	-0.10	17.6	8.21	1.28	1.21	0.15	0.18	0.05	0.12	-0.11
2230	6.88	-0.10	17.5	8.22	1.34	1.31	0.15	0.20	0.05	0.14	-0.11
2300	6.66	-0.44	17.4	8.24	1.58	1.46	0.15	0.22	0.05	0.14	-0.47
2330	6.24	-0.84	17.3	8.26	2.02	1.80	0.30	0.54	0.05	0.16	-1.17
2400	5.70	-1.08	17.2	8.28	2.58	2.25	0.30	0.68	0.05	0.18	-1.53
0030	5.49	-0.42	17.1	8.29	2.80	2.69	0.30	0.81	0.05	0.20	-0.98
0100	5.39	-0.20	16.9	8.31	2.92	2.86	0.30	0.86	0.05	0.20	-0.81
0130	5.29	-0.20	16.6	8.38	3.09	3.00	0.30	0.90	0.05	0.30	-0.75
0200	5.18	-0.22	16.4	8.41	3.23	3.16	0.15	0.47	0.05	0.30	-0.34
0230	5.07	-0.22	16.2	8.47	3.40	3.31	0.15	0.50	0.05	0.30	-0.37
0300	4.97	-0.20	16.0	8.49	3.52	3.46	0.15	0.52	0.05	0.40	-0.27
0330	4.90	-0.14	15.8	8.52	3.62	3.57	0.15	0.54	0.05	0.40	-0.23
0400	4.83	-0.14	15.6	8.56	3.73	3.67	0.15	0.55	0.05	0.50	-0.14
									Average	0.26	-0.56

$$\frac{\Delta c}{\Delta t} = K_2D - K_1L - N + (P-R)$$

(a) C_s = D.O. saturation value (at 4400' El. and 20°C, 8.4 mg/l)
(b) K_1 = 0.012 hr^{-1} (or 0.12 day^{-1}, base 10)
(c) N = calculated oxygen consumption in nitrification

Table 9

Calculation of Daytime (P-R) by Finite Difference Method

Time	D.O. (mg/l)	$\frac{\Delta c}{\Delta t}$ $\left(\frac{mg/l}{hour}\right)$	Temp. (°C)	C_s (a) (mg/l)	D (mg/l)	$\overline{D}$ (mg/l)	K_2 (hr^{-1})	K_2D $\left(\frac{mg/l}{hour}\right)$	K_1L (b) $\left(\frac{mg/l}{hour}\right)$	N (c) $\left(\frac{mg/l}{hour}\right)$	(P-R) $\left(\frac{mg/l}{hour}\right)$
0920	8.55		15.1	8.68	0.13						
		0.06				0.05	0.15	0.01	0.05	0.12	0.22
1000	8.59		15.8	8.55	-0.04						
		0.04				-0.09	0.15	-0.01	0.05	0.14	0.24
1030	8.61		16.3	8.46	-0.15						
		0.14				-0.24	0.15	-0.04	0.05	0.14	0.37
1100	8.68		16.9	8.35	-0.33						
		0.22				-0.42	0.30	-0.13	0.05	0.16	0.56
1130	8.79		17.4	8.27	-0.52						
		0.34				-0.65	0.30	-0.20	0.05	0.18	0.77
1200	8.96		18.0	8.18	-0.78						
		0.48				-0.95	0.30	-0.29	0.05	0.20	1.02
1230	9.20		18.6	8.07	-1.13						
		0.62				-1.33	0.30	-0.40	0.05	0.20	1.27
1300	9.51		19.2	7.97	-1.54						
		0.60				-1.71	0.30	-0.51	0.05	0.30	1.46
1330	9.81		19.4	7.92	-1.89						
		0.58				-2.09	0.15	-0.31	0.05	0.30	1.26
1400	10.10		20.2	7.80	-2.30						
		-0.18				-2.28	0.15	-0.34	0.05	0.30	0.51
1430	10.01		20.5	7.75	-2.26						
		-0.52				-2.16	0.15	-0.32	0.05	0.40	0.25
1500	9.75		20.9	7.69	-2.06						
		-0.52				-1.98	0.15	-0.30	0.05	0.40	0.23
1530	9.49		21.5	7.60	-1.89						
		-0.52				-1.80	0.15	-0.27	0.05	0.50	0.30
1600	9.23		22.1	7.52	-1.71						
									Average	0.26	0.65

$$\frac{\Delta c}{\Delta t} = K_2D - K_1L - N + (P-R)$$

(a) C_s = D.O. saturation value (at 4400' E. and 20°C, 8.4 mg/l)
(b) K_1 = 0.012 hr^{-1} (or 0.12 day^{-1}, base 10)
(c) N = calculated oxygen consumption in nitrification

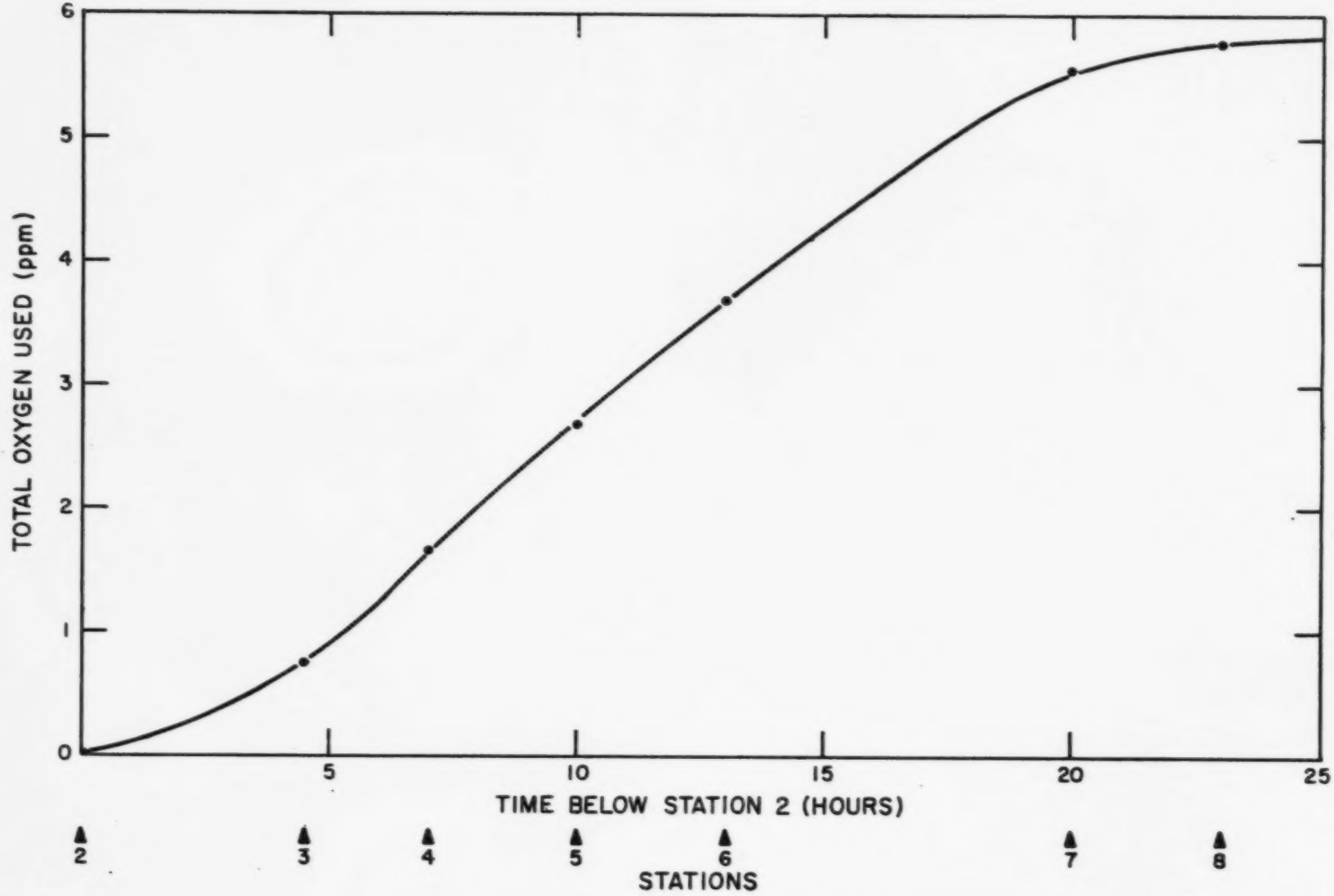
for each half hour in the six and a half hour time of flow from the Reno outfall to Station 4. In this case, all of the (P-R) values were negative which indicates that the respiratory uptake of the algae in the stream exceeded the output of oxygen by photosynthesis as might be expected, since the total time of flow took place during hours of darkness. A similar calculation for Figure 8 is shown in Table 9. In this case, the (P-R) values were all positive indicating that during the daylight hours oxygen output by photosynthesis exceeds the respiratory uptake resulting in the addition of oxygen to the stream.

In Tables 8 and 9 K_2 values were obtained by the use of the O'Connor-Dobbins reaeration formula for non-isotropic turbulence.[8] The information needed for applying this formula was obtained by taking cross sections of the stream at more than 30 locations in the five-mile stretch being studied or at about 800-foot intervals. The calculated K_2 values in Tables 8 and 9 represent median values for the cross sections in the three somewhat distinct substretches of the stream. K_2 values were also calculated by the methods of Velz,[9] Churchill,[10] and Krenkel.[11] While both the Velz and O'Connor-Dobbins formulations yielded similar results, the latter was selected since it appeared to be more responsive to observed changes in stream turbulence conditions. The Churchill formula gave much higher results while the Krenkel formula, employing the coefficient of longitudinal diffusion, was up to three orders of magnitude higher than any of the others.

As can be seen from the calculations in Tables 8 and 9, the selection of a K_2 value has a very pronounced effect on the calculated values

of (P-R). The necessity of having to rely on a formula for K_2 is probably the principal drawback to the use of this method. Values of K_1L shown in the tables were calculated from stream and laboratory data as mentioned previously. The N column represents oxygen consumed in nitrification, that is, the conversion of ammonia nitrogen to nitrite and then to nitrate nitrogen. This value was calculated using Equation 1 together with the observed rate of disappearance of ammonia and nitrites from the stream. It was assumed in these calculations that the ammonia was converted to nitrite and then nitrate before being utilized by organisms in the stream. Thus, the inorganic nitrogen lost from the stream mentioned previously was assumed to have taken place in its most oxidized state as nitrates. The rate of oxygen uptake due to nitrification was taken as the slope of the plot in Figure 9. It is interesting to note that the shape of this curve is very similar to that of curve D in Figure 6 which represents nitrification as it occurs in the laboratory BOD bottle. While the curve shapes are similar, the nitrification reaction in the stream apparently takes place at a much faster rate requiring but five or ten per cent of the time required in the bottle.

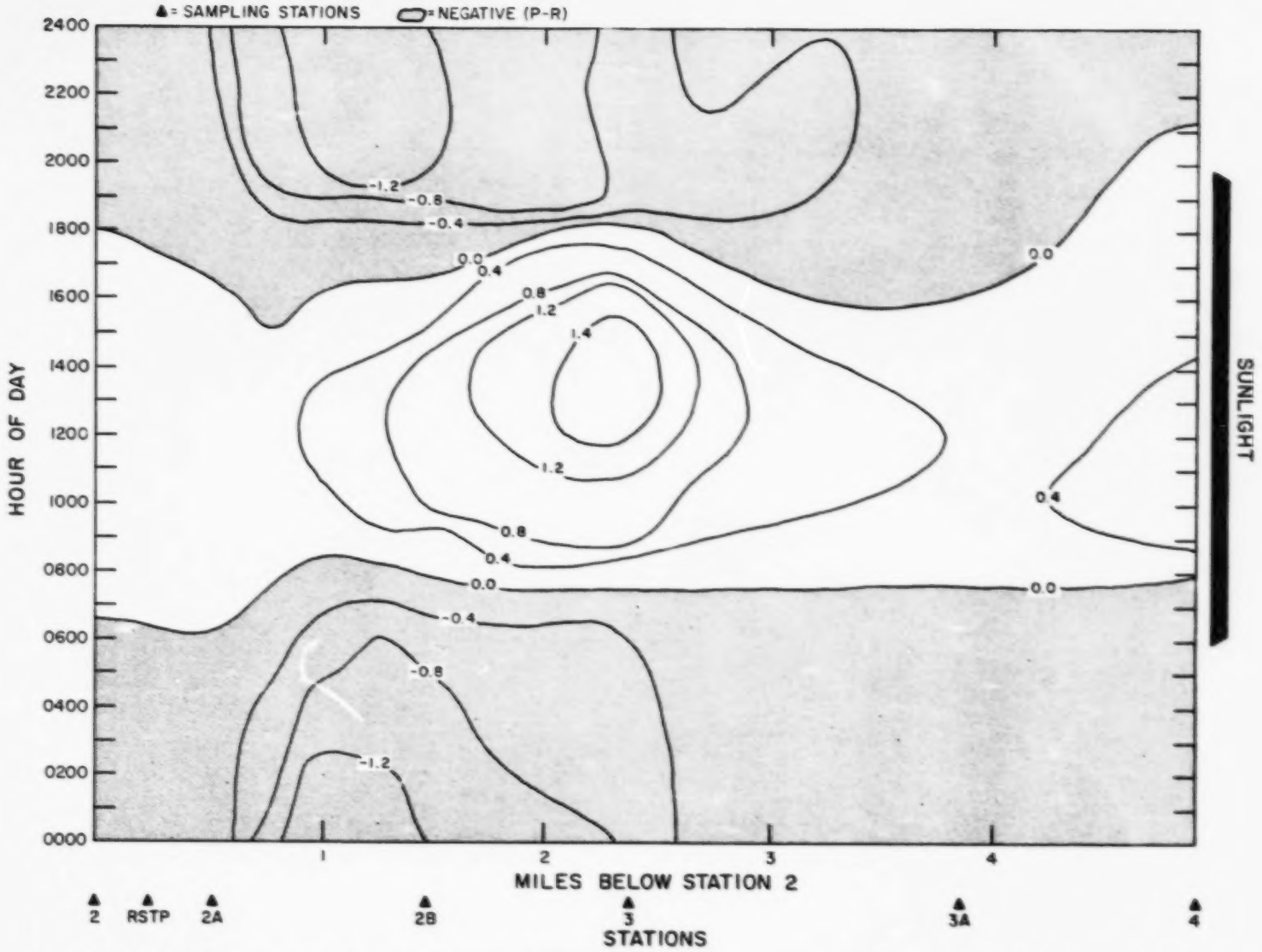
The results obtained from the analyses in Tables 8 and 9 are values for (P-R) for each half hour of the day and at 13 locations equally spaced in time from the Reno outfall to Station 4. These 312 values have been plotted on Figure 10 where contours of equal (P-R) values have been drawn. The location in the stream and the time of day of maximum photosynthetic activity can be readily identified in Figure 10. A vertical section through this figure at any station such as that shown in Figure 11 for a



28a

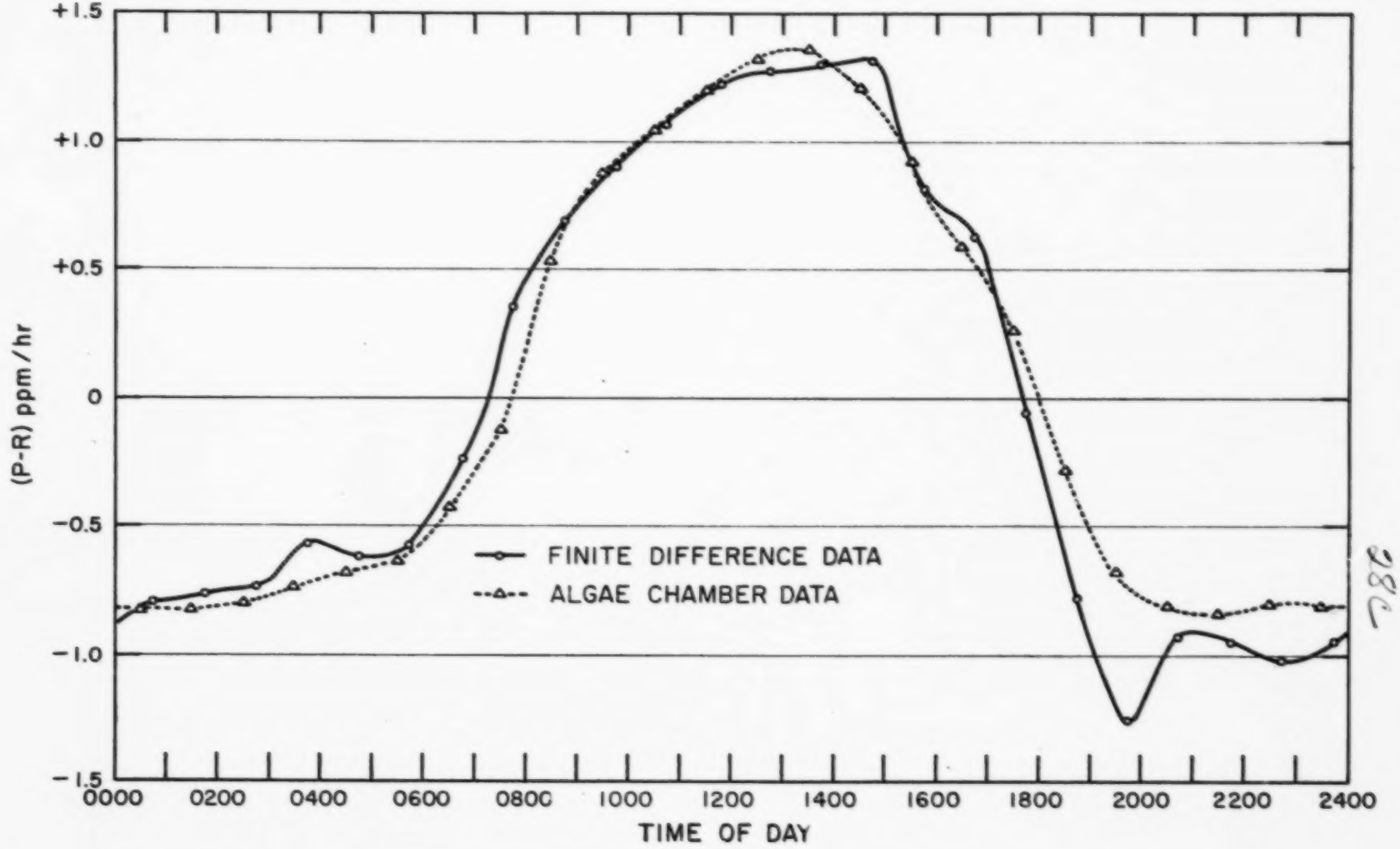
CALCULATED OXYGEN CONSUMPTION BY NITRIFICATION

FIGURE 9



NET OXYGEN ADDED BY PHOTOSYNTHESIS (P-R) ppm/hr. FINITE DIFFERENCE METHOD

FIGURE 10



DIURNAL VARIATION OF (P-R) IN TRUCKEE RIVER NEAR STATION 2B

FIGURE 11

location 1.7 miles below Station 2 shows how photosynthetic activity varies throughout the day at a given station.

The second method used for evaluating (P-R) employed an algae chamber of the type shown in Figure 12. The chambers were constructed from 1/4" plexiglass and were 24" long, 8" wide, and 4" deep. A vertical lengthwise baffle was inserted between the top and bottom of the chamber and a 3" space was left at each end for circulation of water. At one end a submersible pump was installed to produce controlled velocities in the chamber. The open sides and end of the chamber were sealed during a test with six mil polyethylene sheeting which was found to be impermeable to dissolved oxygen. The total capacity of the chamber was ten liters and with the flexible polyethylene sides and ends up to one liter could be removed for dissolved oxygen analyses. Two types of algae were tested in the chambers. A filamentous alga, Cladophora, was cut from rocks, bound together and attached in the chamber. This type of alga was found above Station 2. The second type, Oscillatoria, was predominant in the stretch from Station 2 to Station 4 where it was found growing on the bottom of the stream near the banks. Pieces of the Oscillatoria mat were taken from the stream and placed in Petri dishes. These were covered with cheesecloth and placed in the stream. After 24 hours the alga covered the entire dish. All test results given in this report refer to tests conducted using the Oscillatoria.

In conducting a test the algal-covered dish was placed in the chamber which was secured in the stream at a depth of 12" to 18" below the water surface. The ends of the chamber initially were open to allow the

stream water to flush the contents of the chamber. The polyethylene sheeting at the open ends of the chamber was then sealed. The submersible pump within the chamber was operated so as to produce velocities similar to those occurring in the stream at the point of measurement. A sample was removed from the chamber for determination of dissolved oxygen at the time the test was started. At the end of a test a sample was removed from the chamber and analyzed for D.O. content. Tests of one to two hour's duration were conducted during various periods of the day and at different stream locations to obtain the diurnal variations in the rate of D.O. production and consumption by the stream algae. Final test results are expressed in milligrams of oxygen per hour per unit area of algae. From these results the (P-R) values to be used in the oxygen sag formula can be computed in the following manner:

$$(P\text{-}R)\ \text{mg/l/hr} = \frac{\Delta\ O_2\ (\text{mg/hr/sf algae}) \times A\ (\text{sf})}{V\ (\text{liters})} \qquad (5)$$

This formula was applied to each of the more than 30 stream cross sections previously mentioned.

For each stream reach between two cross sections, the water volume (V), and the area of the bottom covered by algae (A), were calculated. The area of algal coverage was calculated as the total bottom area within 18" of the water's surface, since Oscillatoria was observed to partially cover the bottom until the depth exceeded approximately 18". This area was multiplied by the per cent of the bottom covered by the Oscillatoria which was estimated by inspection of each stream reach.

Figure 12

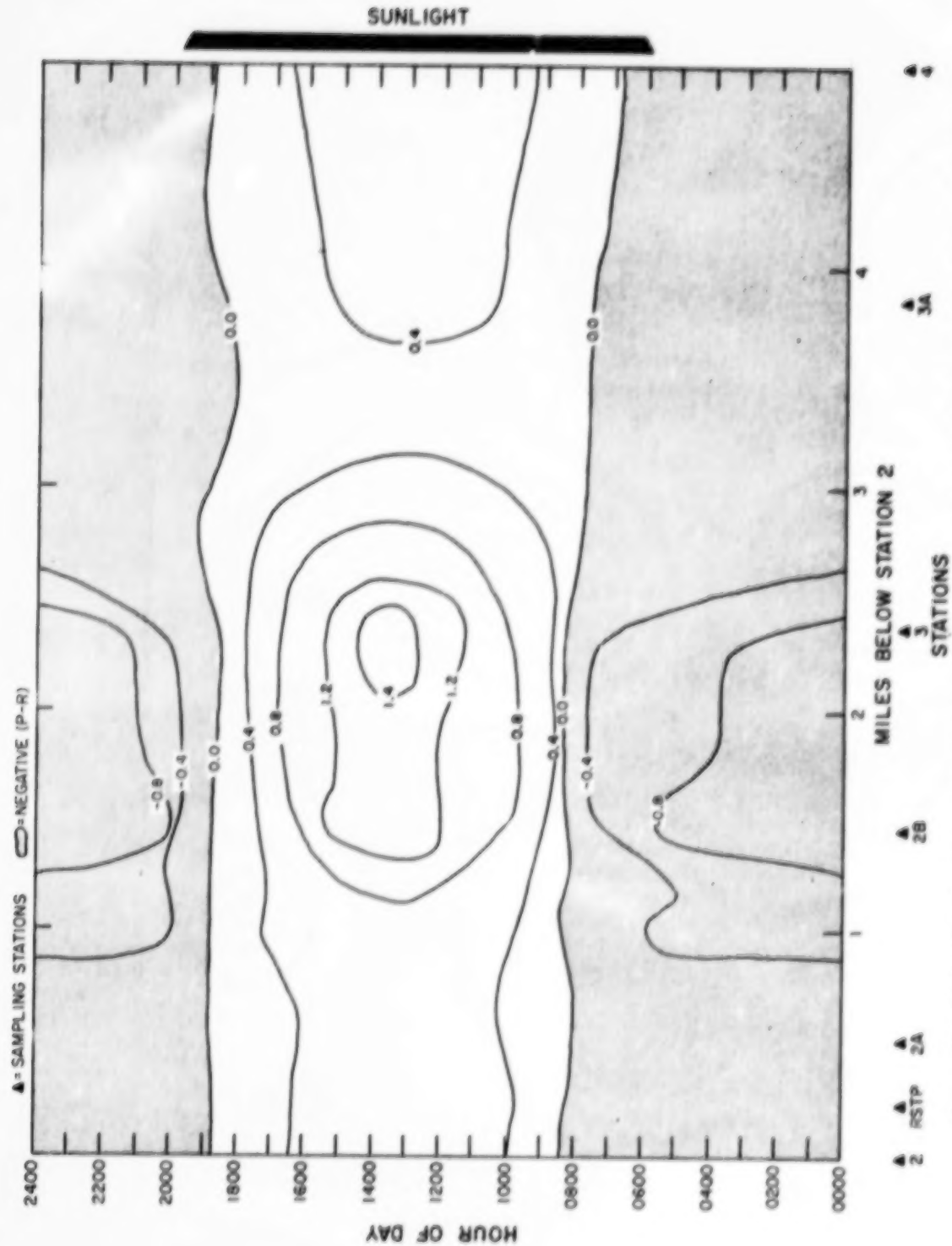
Algae chamber as it appears
in place in the river.

Since the test chamber was initially filled with river water, the D.O. variations observed were due in part to the deoxygenation of organic materials and nitrification taking place in the stream water with which the chamber was filled as well as to the algae placed in the chamber. It was necessary, therefore, to correct the observed results for the known carbonaceous and nitrogenous oxygen utilization that occurred during the test. The results of these computations are presented in Figure 13 as a plot of (P-R) in milligrams per liter per hour versus time of day and location in the stream. Since the data presented in Figure 13 have been corrected for carbonaceous and nitrogenous oxygen demand, Figures 11 and 13 should be directly comparable and are indeed quite similar.

Both figures show the location, magnitude, and time of day of peak net photosynthetic oxygen production to be the same, i.e., 1.4 mg/l per hour at about one o'clock in the afternoon located just above Station 3. The time of day at which photosynthetic production just equals respiratory consumption is similar on both figures and occurs in the morning about one and a half hours after sunrise (7:30 a.m.) and in the late afternoon at about an hour and a half before sunset (5:30 p.m.). The only major difference appears to be that the finite difference method gave greater peak net respiration rates than did the algal chamber method. The major shortcoming of the finite difference method lies in the necessity for estimating K_2. It is also necessary to interpolate the dissolved oxygen curve between stations as in Figures 7 and 8. A major weakness of the algal chmaber method lies in the estimate of areal coverage of algae although the magnitude of this error can be minimized if the estimate is

made by experienced biologists. In addition, the algal chamber does not measure any other benthic demand that may be present in addition to the test algae placed in the chamber. In this case, because of the preponderance of Oscillatoria and the absence of significant sludge deposits, it is not believed that any other significant benthic demand existed. Since the algal chamber was filled with river water, any free-floating phytoplankton would also be included in the chamber during the test period. If plankton were present in significant amounts, their production and respiration would have to be handled somewhat differently in the analysis of data since they move along with the stream flow and are not fixed in place as are attached algae. In this case, control tests without Oscillatoria in the chamber confirmed the absence of significant populations of phytoplankton. In both cases correction for oxygen uptake by the carbonaceous BOD was necessary, but this presented no problems, particularly since it was such a relatively small quantity. The correction for oxygen consumed in nitrification, however, was relatively large and errors in making this correction could affect the results significantly. In future work with an algal chamber it appears desirable to obtain nitrogen concentrations before and after the test period so as to permit a more complete understanding of the oxygen uptake mechanisms taking place.

A vertical section through Figure 13 representing (P-R) values at 1.7 miles below Station 2 in the area of maximum photosynthetic activity yields the plot shown in Figure 11. At this particular location the curves produced by the two different methods followed each other quite closely. A statistical analysis comparing the two methods yielded a



NET OXYGEN ADDED BY PHOTOSYNTHESIS (P-R) ppm/hr. ALGAE CHAMBER METHOD

FIGURE 13

correlation coefficient, r = 0.96. This excellent agreement is typical of that obtained throughout the area of highest productivity. Because of this agreement of the estimates made by independent means, it is concluded that either of these methods can be expected to produce a useful evaluation of (P-R).

Curves such as those in Figure 11 may be analyzed to yield the total amount of oxygen produced and consumed by photosynthetic and respiratory activity for each stream reach being studied. Using the algal chamber data plot (Figure 11) a line may be drawn from the minimum pre-sunrise value horizontally to the minimum post-sunset level. The area between this line and the curve will be equal to the total daily oxygen production by photosynthesis in milligrams per liter for the stretch which this curve represents. A similar estimate for oxygen consumption by respiration may be obtained by making the assumption, as is usally done, that respiration is constant throughout the day. The minimum (P-R) value observed during the hours of darkness in milligrams per liter per hour multiplied by the 24 hours of the day will give the total oxygen uptake in milligrams per liter per day for the stretch. This has been carried out for the curve in Figure 11 with the result that P was found to equal 20.7 mg/l/day while R was equal to 20.9 mg/l/day. The ratio of $\frac{P}{R}$ in this case is equal to 1. By miltiplying the photosynthetic production of oxygen in milligrams per liter times the volume of the stream in the section the total pounds of oxygen produced per day may be calculated. This was done for all of the sections of the stream in the five-mile stretch between the Reno outfall and Station 4, and it was found that total photosynthetic

oxygen production was equal to 3,072 pounds per day. This was equivalent to 72.5 pounds per acre of stream surface per day. In a similar way the oxygen uptake by respiration of the algae was found to be 2,765 pounds per day or 65.4 pounds per acre of stream per day. The $\frac{P}{R}$ ratio for the entire stretch of stream, therefore, was 1.1. A $\frac{P}{R}$ ratio in excess of unity indicates that the algal crop in the stream was undergoing growth and had not yet reached a steady state equilibrium condition. A possible explanation can be found in the previously mentioned bulldozer operations which took place in this stretch of the stream during the week previous to the study. At that time algae was destroyed in many parts of this section of the stream by the scraping action of the bulldozer blade on the stream bottom. It was expected that this would greatly reduce the amount of photosynthetic production that might be found during the study. However, the regrowth of the algae was quite rapid.

It should be immediately evident that the large amount of oxygen produced by photosynthesis, namely, 3, 072 pounds each day or 11.8 mg/l/day in the stretch is of little benefit to the net oxygen balance in the stream. The oxygen uptake by these same organisms and other stream biota was very nearly equal to the oxygen produced by aquatic plants so that over a day's time little or no net gain was recorded. Of even greater importance to the stream oxygen balance, however, is the fact that the oxygen addition takes place only during hours of daylight while the respiratory uptake is continuous. This accounts for the large diurnal variation in stream D.O. with maximum values during the day and minimum values at night. But this still is not the entire picture. The water receiving

this "asset" of oxygen from photosynthesis has, of course, moved downstream with its oxygen-rich waters as daylight ends. The water entering the head of the stretch at sunset does not contain the oxygen produced in that stretch during the daylight but must nevertheless satisfy the "liability" of the respiratory demands of the algae fixed to the stream bottom. The stream reacts to this demand much as it would to a sludge deposit. In this case, to a deposit equivalent in terms of oxygen to that which would be produced by the discharge of raw sewage from a community of 50,000 persons. The result is a sudden drop in stream D.O. which continues until the water has passed through the stretch completely or sunrise occurs, whichever comes first.

PREDICTION OF FUTURE CONDITIONS

Dissolved oxygen has been used as a measure of water quality for many years. Most regulatory authorities have developed standards for minimum stream dissolved oxygen levels not only to prevent the development of nuisance conditions which occur when the D.O. is exhausted, but also to provide a favorable aquatic habitat for the particular species of fish which may be of importance in a particular stream. Minimum D.O. levels of four or five milligrams per liter are often considered to be satisfactory for most warm water species of fish. However, the dissolved oxygen requirements of the more desirable cold water game fish such as salmon and trout, particularly for spawning, are more demanding. Minimum D.O. levels of 6 mg/l or higher are recognized as being necessary to protect these salmonoid fishes and experience has shown that they are not usually found in streams where levels remain below 4 or 5 mg/l.[12] These

standards generally refer to levels below which the stream dissolved oxygen concentration is not permitted to fall. Attention has only recently been directed toward evaluating the effects of widely varying levels of D.O. during a 24-hour period as found in the Truckee River on the propagation of a particular species of fish.[13] These studies indicate that the growth rates of fish subjected to fluctuating D.O. concentrations are dependent not on the daily mean value but on the dissolved oxygen minima occurring at night or early in the morning. The depressant effect on growth was comparable to that observed when the fish were subjected to a constant dissolved oxygen concentration about 1 mg/l higher than the mean daily minimum. It is known that the survival of salmon larva hatched at low D.O. levels is significantly below that at optimum conditions. The avoidance of waters of low D.O. content by cold water fishes has also been demonstrated. In addition, the very dense algal growth which produces these wide D.O. variations in the Truckee River excludes other more desirable fish food organisms from the stream. The combination of all of these factors tends to reduce quite severely the suitability of such a stream for the propagation of desirable cold water species of fish. Although no specific survey of fish was attempted on the Truckee River, it was concluded from observations and conversations with the local populace that successful trout fishing could ordinarily be expected only above the point of entry of the Reno Sewage Treatment Plant discharge. Thus, it seems reasonable to expect that improvements in stream D.O. conditions would increase the value of the Truckee River below Reno as a trout fishery.

The data already presented permit a better understanding of the various factors which influence dissolved oxygen content in the Truckee River. This information can also provide the basis for making estimates of dissolved oxygen conditions which can be expected under conditions of waste loading and stream flow other than those existing during the field surveys. This type of information can be particularly useful in future planning for pollution abatement facilities and makes it possible to estimate what improvement could be expected from an increase in the degree of waste treatment or an increase in stream flow rates.

The oxygen sag formula, modified by the addition of the term to reflect the effects of photosynthesis (Equation 3), has been used for estimating purposes. As a first step, values were assigned to all of the variables and constants in the equation based on observed survey findings except for K_2. The equation was then solved by trial and error to find a suitable mean K_2 value for use over the entire stretch being considered. Although (P-R) and N, the nitrification demand, were observed to vary downstream, for ease of computation in these calculations they were treated as a constant using average values calculated for the entire reach. The mean value of K_2 which best fit the stream data in this situation was found to be 0.14 per hour (Base e).

In order to find K_2 for use at other stream flows, the following two relationships were used:

$$K_2 = f(H^{-1.25}) \quad \text{where } H = \text{depth (ft.)} \tag{6}$$

$$H = 0.47Q^{0.274} \tag{6a}$$

The first is taken from the O'Connor-Dobbins[8] equation for K_2 and the second was found to fit the U. S. Geological Survey cross section data quite well at the Reno Gage just above Station 2. Combining these two expressions the following formula for K_2 as a function of flow was obtained:

$$(K_2)_2 = (K_2)_1 \left(\frac{Q_1}{Q_2}\right)^{0.342} \tag{7}$$

This expression can be solved to show, for example, that a 50% reduction in stream flow will bring about a 27% increase in the value for K_2.

As in the first survey report[1] it is assumed as a first approximation that the level of biological activity would remain unchanged at other stream flows. However, previously it was assumed that the product of the respiration rate and the stream flow was a constant. To be more precise it is the product of the respiration rate (R, mg/l/hr) times the total water volume in the stretch (V) which may be assumed to be equal to a constant, namely, 2,765 pounds per day. The relationship of the volume of water in the stretch to the volume rate of flow can be obtained by combining the following expressions:

$v = aQ^b$ v = mean velocity (fps) (8)

$Q = Av$ A = cross sectional area (sf) (8a)

$V = LA$ L = length of stretch (ft.) (8b)

The first of these was also obtained from data on the Reno Gage where it was found that the constant b is equal to 0.645. From the above the equation for the volumetric rate of oxygen consumption by respiration as

a function of flow is given by:

$$R_2 = R_1 \left(\frac{Q_1}{Q_2}\right)^{0.355} \qquad (9)$$

From this expression it can be found that a 50% reduction in stream flow causes R to increase by 28%.

The time of passage through the stretch is a third parameter which will change significantly with changes in stream flow. By combining the equation for stream velocity given above with the fact that the length divided by the time of flow is also the mean velocity the following expression for time of flow (T) as a function of stream flow can be obtained:

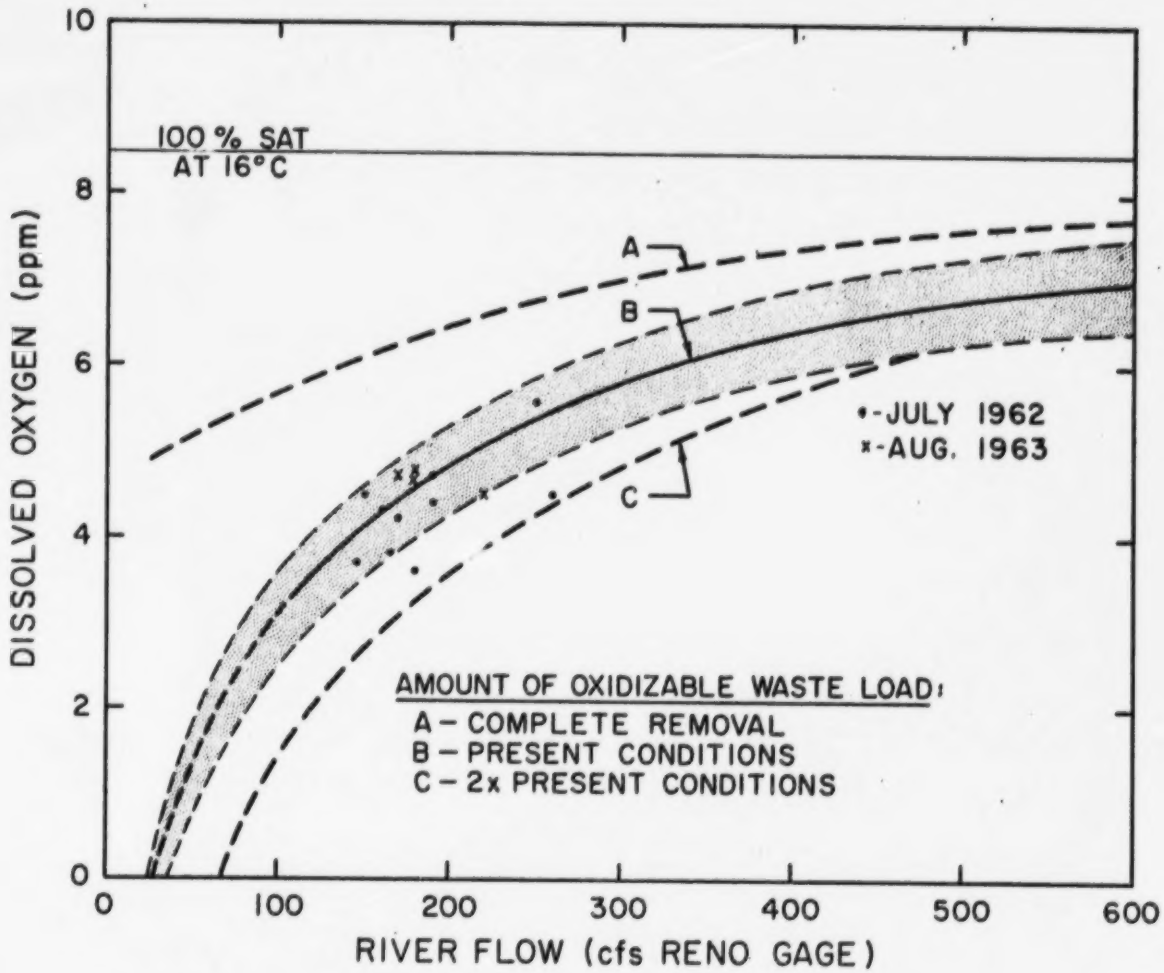
$$T_2 = T_1 \left(\frac{Q_1}{Q_2}\right)^{0.645} \qquad (10)$$

This indicates that a 50% reduction in stream flow will increase the time of passage this stretch by 56%.

Using the equations developed above together with the modified oxygen sag formula (Equation 4) the minimum daily dissolved oxygen content expected at the end of the stretch of dense algal growth (Station 4) was calculated as a function of stream flow. The results of this calculation are presented in Figure 14. This plot has been expanded to a band 1 mg/l wide to reflect the uncertainty inherent in making such estimates where a constant level of algal activity has been assumed. Actually, the minimum D.O. concentration, even at a constant stream flow, will vary from day to day depending on such environmental conditions as cloud cover, air temperature, and stream turbidity. This accounts in part for the variation in the observed data which are also plotted on Figure 14 from both surveys.

An analysis of the deficit calculations from which Figure 14 was prepared gives an indication of the extent to which the total deficit is due to the various influencing factors. For example, at 100 cfs flow rate approximately 5% of the total daily maximum D.O. deficit is due to the low D.O. in the Reno Plant effluent and an equal amount is due to the carbonaceous BOD. The remaining 90% of the total deficit results from nitrification of ammonia and nitrites and alagal respiration in about equal amounts. Thus, it can be seen that further reduction of carbonaceous BOD only by the treatment plant would have a relatively small effect on raising the minimum D.O. at Station 4. If treatment were increased so as to accomplish nitrification within the plant thus greatly reducing the ammonia in the plant effluent as well as the carbonaceous BOD, it would appear that the downstream D.O. deficit could be reduced by a maximum of 50%. The major portion of the total deficit which still remains is caused by algal respiration and this can be eliminated only by the removal of a substantial proportion of the nitrogen and phosphorus from the plant effluent.

The series of curves presented in Figure 14 give some indication of the estimated effect of changes in the oxidizable waste load upon the daily minimum D.O. in the river. This oxidizable waste load is made up of carbonaceous BOD and the reduced forms of nitrogen, primarily ammonia, present in the waste effluent. The plots in Figure 14 indicate that if this waste effluent were to receive a higher degree of treatment resulting in the further reduction of BOD and nitrification of much of the ammonia within the plant to the nitrate form an improvement in stream D.O.



PREDICTED DAILY MINIMUM DISSOLVED OXYGEN
STATION 4 – TRUCKEE RIVER

FIGURE 14

conditions could be obtained. At 100 cfs, for example, the minimum daily stream D.O. at Station 4 might be raised by an amount approaching 2 - 3 mg/l. This improvement in treatment, however, would not significantly diminish the amount of nitrogen and phosphorus being added to the stream and the present dense algal growth would not be eliminated. Moreover, the conversion of nitrogen from the ammonia to the nitrate form before discharge might conveivably bring about a change in the flora of the stream. What this change might be is not predictable nor is it possible from field observations to infer whether this change would be beneficial or detrimental to the stream oxygen conditions. It does not seem probable, however, that any significant change in plant respiration rates could be expected or that the present dense algal coverage would be made more severe.

If it were desired to maintain daily minimum stream D.O. levels above, say, 6.5 mg/l in the interest of promoting a more favorable aquatic habitat for trout, it is estimated that, under present conditions of waste loading, stream flows in excess of 500 cfs would be required. Even if the waste effluent were totally oxidized, which may be an excessively expensive objective, dilution stream flows in excess of 200 cfs would still be required. In the absence of practical methods of nutrient removal from the waste the only other alternative to achieve such a D.O. objective would be to withhold the waste effluent from the river.

SUMMARY AND CONCLUSIONS

Based on surveys conducted in July 1962 and August 1963 the following conclusions have been reached regarding the quality of the Truckee River near Reno.

The Truckee River above and within the city of Reno possesses a balanced biological environment and supports a valuable population of trout and other cold water species of game fish. The river waters contain very low levels of the nutrients nitrogen and phosphorus and exhibit only slight diurnal fluctuations in dissolved oxygen. The daily minimum dissolved oxygen level does not usually drop much below 7 mg/l. In the five-mile stretch below the entry of the Reno Sewage Treatment Plant effluent the inorganic nitrogen and phosphorus levels increase sharply and the stream bottom is covered with a dense growth of the blue-green alga Oscillatoria. Very large diurnal fluctuations in stream dissolved oxygen occur with daily minimum values of about 5 mg/l being found throughout a 25-mile stretch downstream from Reno at flows near 200 cfs. The lowest daily minimum D.O. values are commonly found at a point five miles below the Reno discharge (Station 4). The Truckee River below Reno is little used by trout fishermen and contains a large population of carp. The daily addition of 3,000 lbs. of phosphorus and 2,000 lbs. of nitrogen to the river by the two municipal sewage treatment plants and lesser amounts by two irrigation return drains is considered to be the primary factor causing these changes in the Truckee River below Reno. The nitrogen and phosphorus, possibly together with other growth-stimulating materials present in trace amounts in the waste discharges, support the dense algal growth found in the five-mile stretch below Reno. These organisms in turn produce large quantities of oxygen by photosynthesis during daylight hours causing supersaturated dissolved oxygen levels in the river during mid-afternoon. The respiratory requirements for oxygen of these same algae greatly reduce the stream D.O. content at night resulting in daily minimum values at Station 4 of 3.5 to 4.5 mg/l at stream flows near 150 cfs.

The oxidizable waste material discharged by the Reno plant also contributes to the total oxygen deficit in the river. Both carbonaceous BOD and ammonia are oxidized in the stream. The oxygen required for conversion of the ammonia to nitrite and to nitrate appears to exceed that utilized in oxidation of the carbonaceous material by a factor of two or three. Because of this intensive nitrification the results of five-day BOD analysis of river samples collected below Reno reflect both the first and second stage demand. Interpretation of such results cannot be made in the usual way as when nitrification is absent. Pasteurization and reseeding of BOD samples appears to satisfactorily inhibit nitrification during the five-day test period and is a useful modification of the standard test procedure. As a first approximation, it can be assumed that 40% of the five-day BOD value is due to the carbonaceous demand.

The daily minimum dissolved oxygen concentration found in the Truckee River below Reno is also influenced by the magnitude of the river flow. It has been estimated that under present conditions of waste loading and at flows below 100 cfs (Reno Gage) daily minimum D.O. values below 3 mg/l can be expected. Some noticeable improvement in the minimum D.O. of the river could be achieved by more extensive treatment within the Reno plant to produce a more nitrified plant effluent. The effect that this change in the form of nitrogen might have on the type of algae presently found in the river is not known. A further increase in the oxidizable waste load discharged to the river would lower still further the daily minimum dissolved oxygen concentration in the Truckee River below Reno.

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